Multi-muon events at CDF

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on behalf of the CDF collaboration

Rencontres de Moriond on
QCD and High Energy Interactions
March 17th, 2009

Outline

- Physics motivation:
  - puzzles in *b* production and decays from Tevatron (Run I)
    - Correlated $b\bar{b}$ production, σ_{bb}, higher than Standard Model
    - Di-lepton invariant mass spectrum of b cascade decays
    - Time-integrated mixing probability, $\bar{\chi}$, of b-hadrons larger at Tevatron than at LEP

- Recent results:
  – new and very precise measurement of σ_{bb} agrees with the prediction [PRD 77,072004 (2008)]

- Study of the multi-muon events: arXiv:0810.5357[hep-ex]
  - Analysis leading to the excess of multi-muons
  - Sources contributing to the excess of multi-muons
  - Additional properties of the multi-muon excess

Correlated $b\bar{b}$ cross section

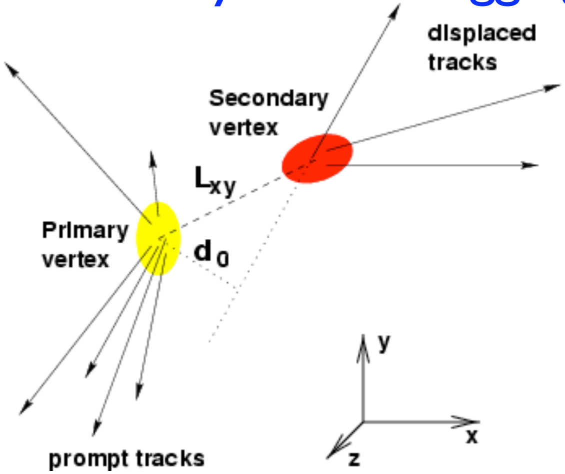
Two b's in the central region with enough p_T.

- Theoretical uncertainty (15%)

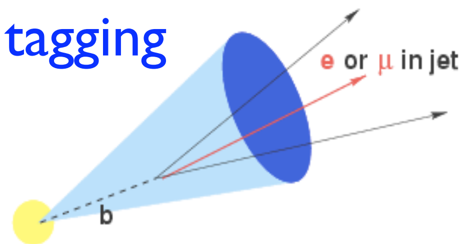
  LO diagrams dominate

  Measurement techniques

  - secondary vertex tagging

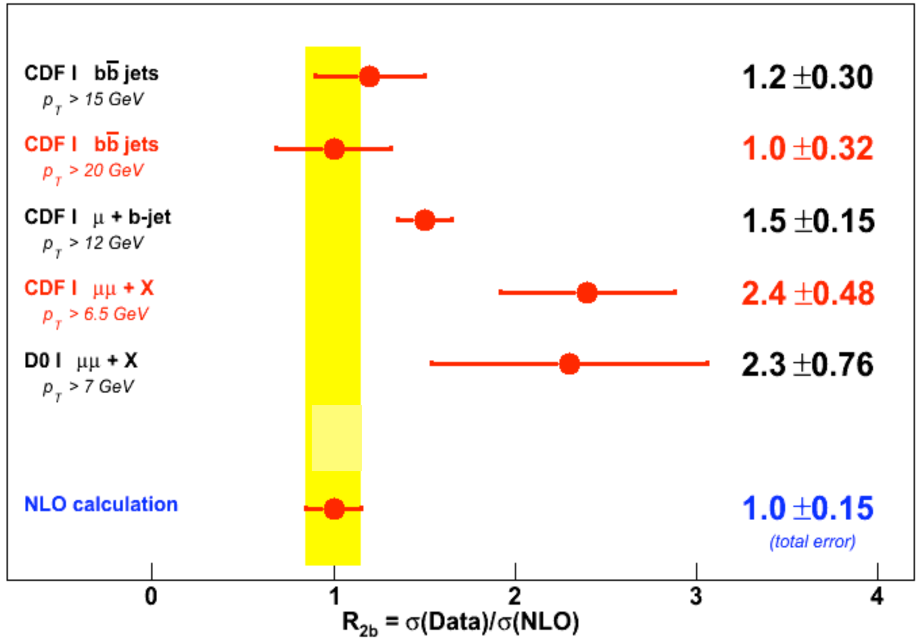


  - muon tagging



$R_{2b}=\sigma_{bb}$ (measured)/σ_{bb} (NLO) (RUN I)

- Vertex tag analyses → $R_{2b}=1$
- Muon tag analyses → $R_{2b}>1$



$$\sigma\left(p\bar{p} \to bb \to llX\right) > \sigma_{NLO}$$

Discrepancy $\propto$ N(μ)

Average time-integrated mixing probability, $\bar{\chi}$

Average time-integrated mixing probability of *b* hadrons, $\bar{\chi}$ measured at the Tevatron is significantly larger than at LEP

0.152±0.013 vs 0.126±0.004 [PRD 69, 012002 (2004)]

$$\boxed{\bar{\chi} = \frac{\Gamma(B^0 \to \bar{B}^0 \to l^+ X)}{\Gamma(B \to l^\pm X)} = \frac{\text{"}same\ sign\text{"}}{\text{"}total\text{"}},\ B^0 = B_d^0\ or\ B_s^0}$$

$$\bar{\chi} = \chi_d f_d + \chi_s f_s$$

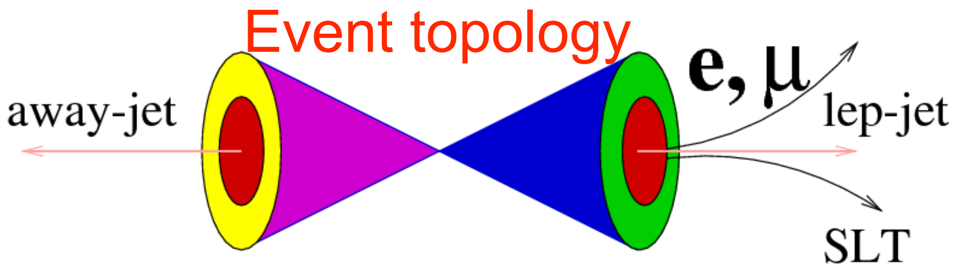
Time integrated mixing parameters χ_d and χ_s well measured

Measurement of $\bar{\chi}$ constraints the fractions, f_d and f_s, of b quark fragmenting into B_d and B_s

PDG: the *b*-hadron mixtures must be different

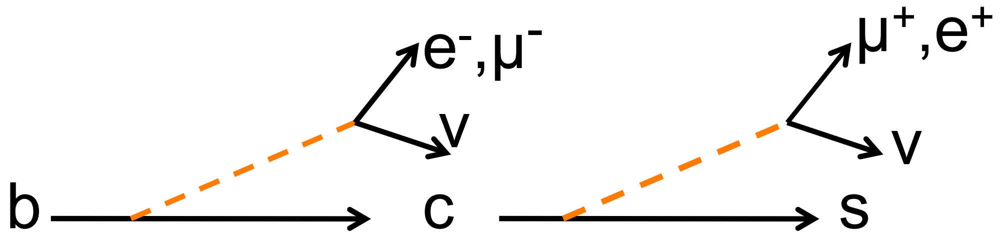
Low mass di-leptons

PRD 72, 072002 (2005)

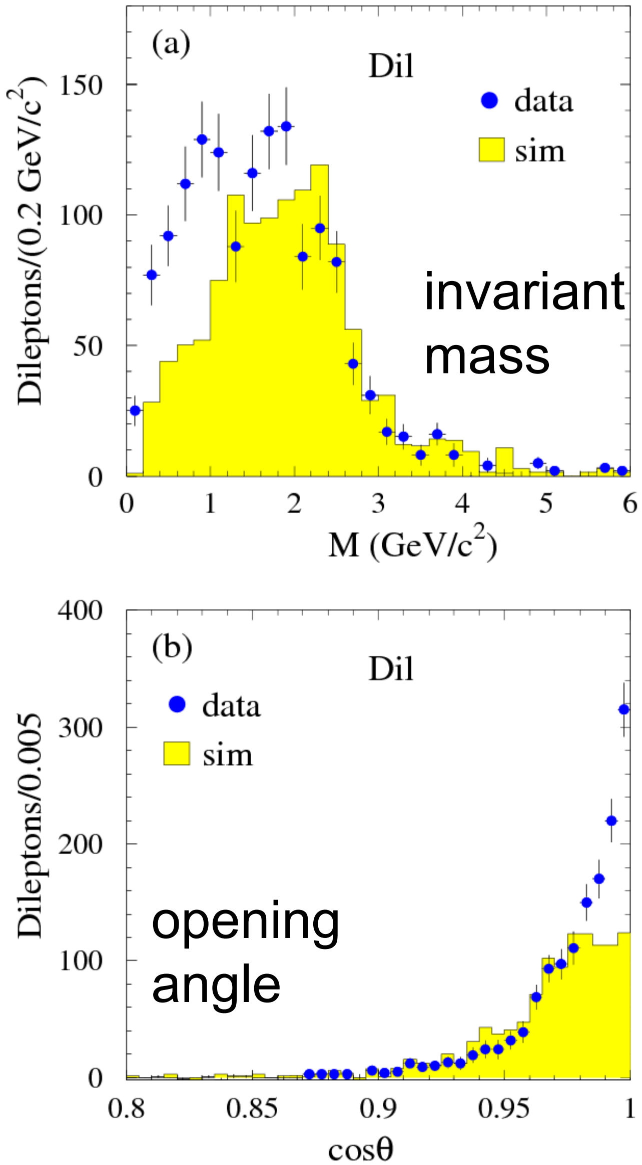


- *B* enriched sample:

  the low mass di-lepton invariant mass is not well modeled by sequential semi-leptonic decays of single *b* quarks



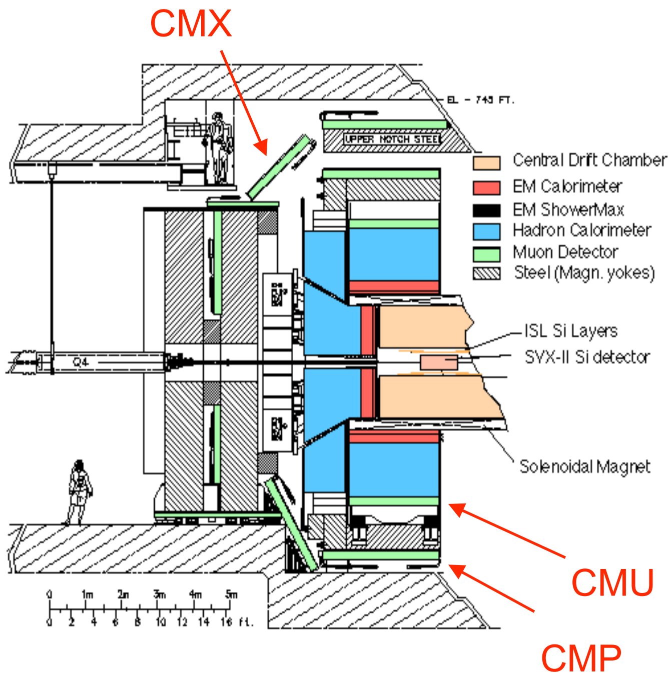
- Simulation: HERWIG+EVTGEN

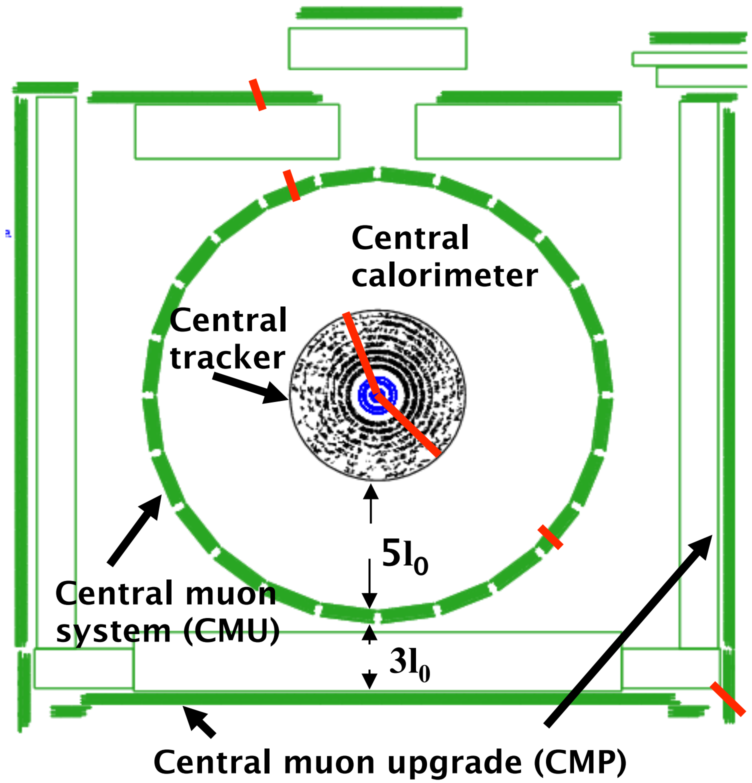


New measurement of $\sigma\left(p\bar{p} \rightarrow b\bar{b} \rightarrow \mu\mu X\right)$

- Event sample: 743k events $\longrightarrow$ 742pb^{-1}

  Defined by a dimuon trigger:
  - Central track with p_T > 3 GeV, $|\eta| < 0.7$
  - Match to stub in CMU and CMP (CMUP)
  - $5 < M_{\mu\mu} < 80$ GeV (no Z's, J/ψ, $b \rightarrow c\mu \rightarrow \mu\mu X$)

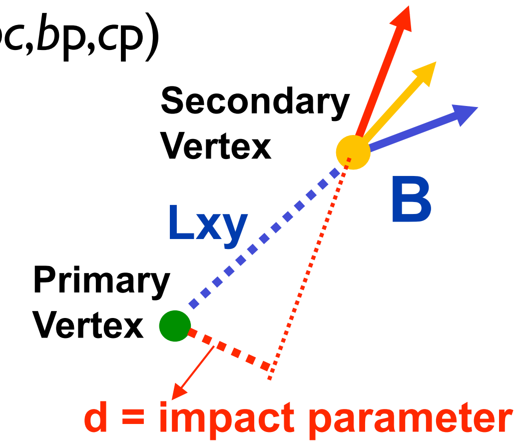


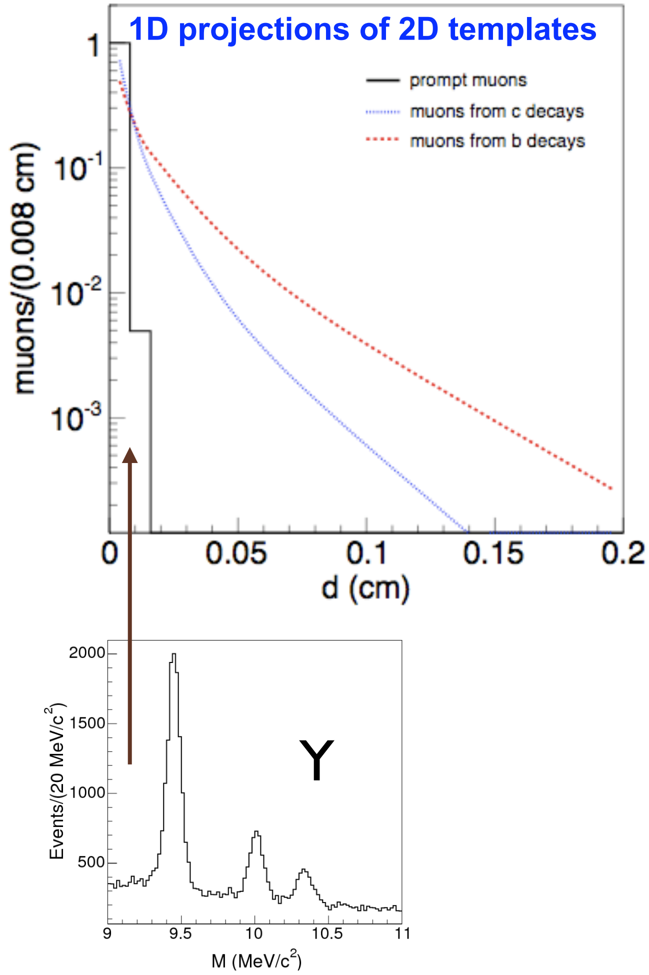


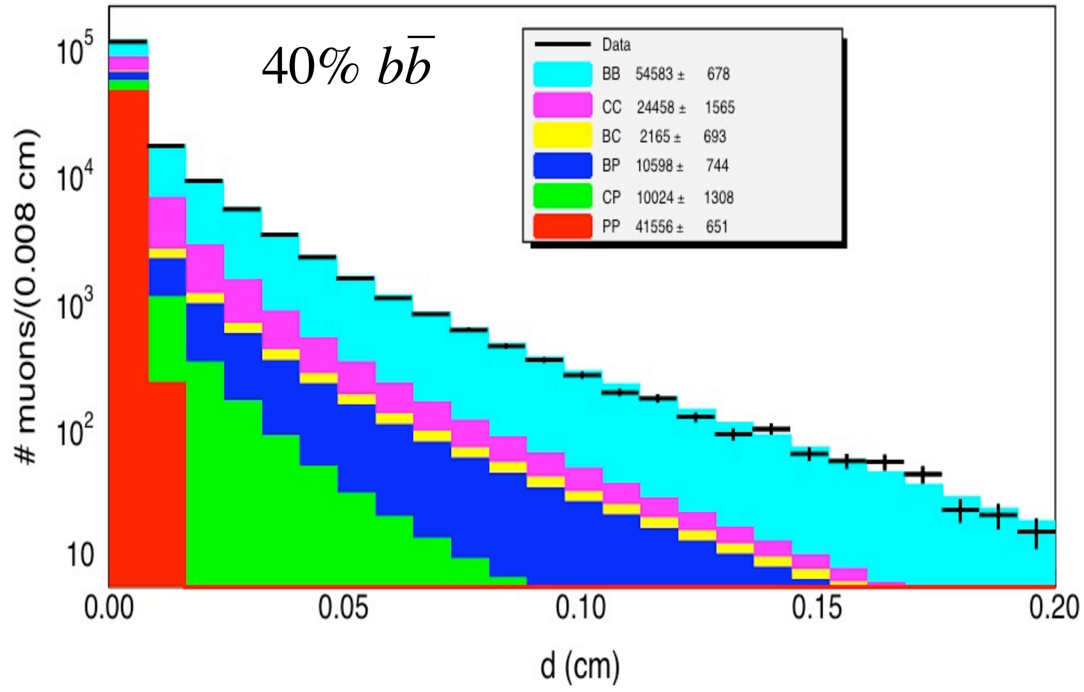
- Known sources of real muons are:
  - $b \rightarrow \mu$ ($c\tau$ = 470 μm), $c \rightarrow \mu$ ($c\tau$ = 210 μm)
  - Prompt muons (Υ, Drell-Yan)
- Known sources of fake muons include:
  - Hadrons punching through calorimeter
  - Decays in flight ($K \rightarrow \mu$, $\pi \rightarrow \mu$)
  - Fake muons can be from prompt or h.f. decays

New measurement of σ_{bb}: The method

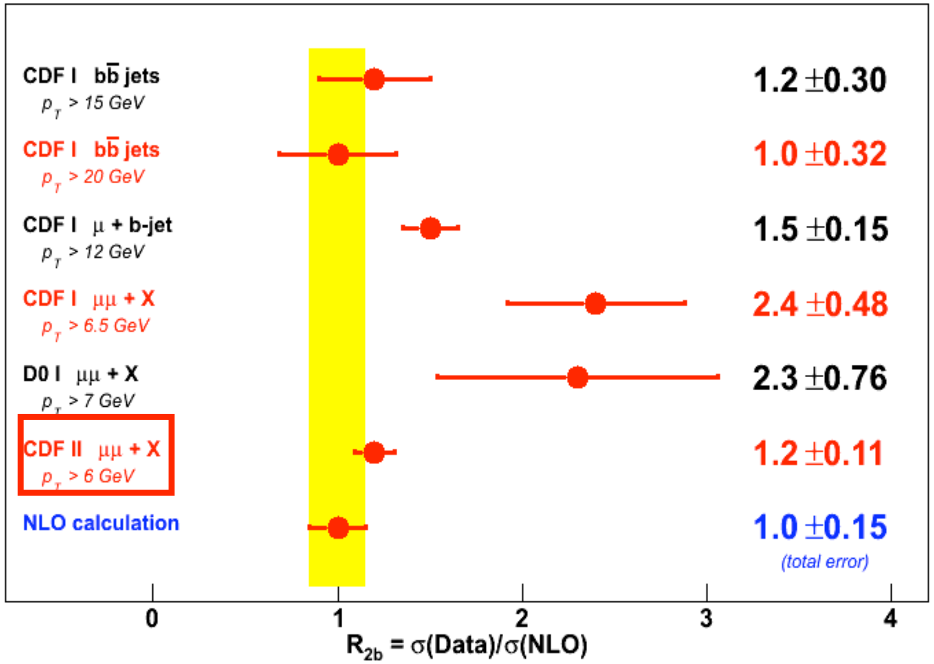
- Extract the sample composition by fitting the observed d_0 distribution of the muons [2D fit - $d_0(\mu_1)$ vs $d_0(\mu_2)$] with the expected d_0 distributions of muons from various sources and for all the combination (*bb*,*cc*,pp,*bc*,*bp*,cp)
- Develop templates for h.f (MC) and Prompt (Υ from data)







New measurement of σ_{bb}: results



- Very accurate
- Appreciably smaller than Run I results

$$\sigma_{b\bar{b}} = 1328 \pm 209 nb \quad \text{NLO}$$

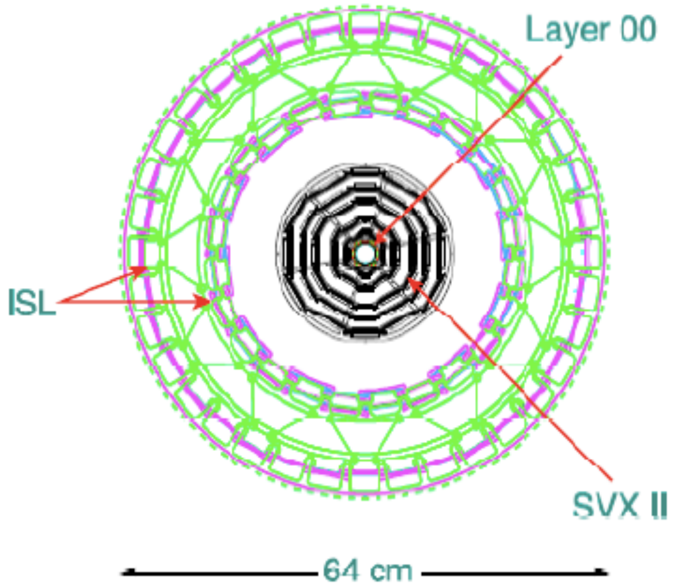
$$\sigma_{b\bar{b}} = 1618 \pm 148 nb \quad \text{Data}$$

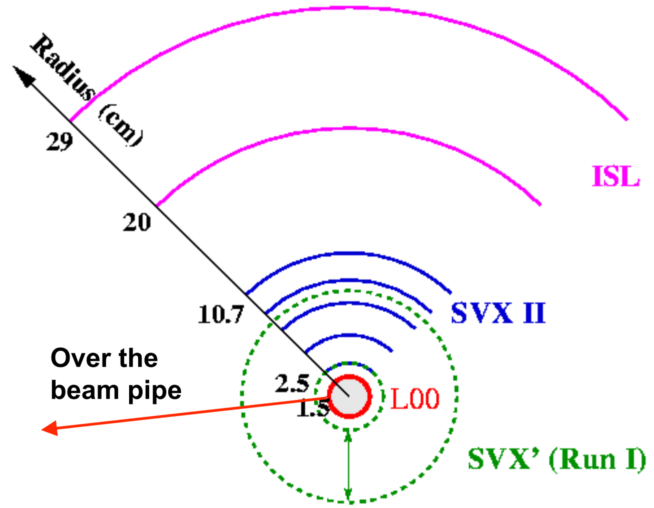
$$\left(p_T^b > 6 GeV \quad |\eta| < 1.0 \right)$$

Investigating the differences: tracking

The highest tracking precision is achieved using hits in the SVX II detector; in this way we can separate muons from *b*'s, *c*'s and prompt sources

SVX II (L00, L0, L1, L2, L3, L4)





Impact parameter resolution:

- 230 μm (COT only tracks)
- 30 μm (COT + ≥ 3 SVX hits)

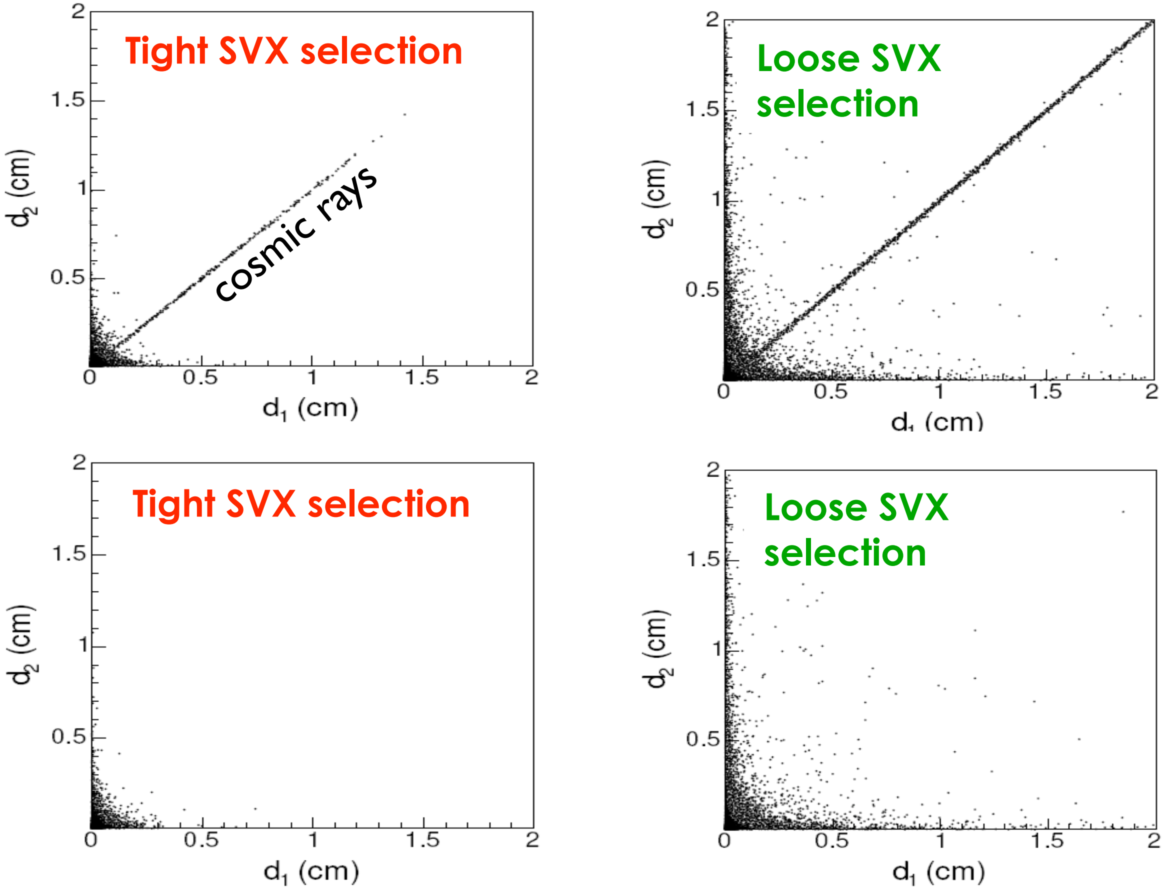
The excellent modeling of the 2 muons impact parameter distribution is obtained only using

- **tight SVX** requirements (hits in L0, L00 and two of the remaining L1-L4 layers)
- L0 and L00 are essential

This selection requires that both muons originate inside the beam pipe

Tracking differences

- Analyses in CDF use **loose SVX** requirements: 3/8(SVX+ISL) layers
  - Muons can originate as far as 10.8 cm from the beam line
- Run I analyses selected muons originating from distances as large as 5.7 cm from the beam pipe
- According to simulation, 96% of QCD events have 2 muons originating inside the beam pipe



➢ Verifying the acceptance of the different Silicon req's:

Use cosmic rays overlapping $p\overline{p}$ collisions:

2 muons back to back clustering along the diagonal of $d_0(\mu_1)$ vs $d_0(\mu_2)$

After cosmic ray removal

$$\varphi_{\mu^-\mu^+} < 3.135 rad$$

SVX selection efficiency

- Evaluate efficiencies using control samples of data
  - Prompt: (25.7±0.4)% using Υ and Drell - Yan
  - Heavy Flavor: (23.7±0.1)% using $B \to J/\psi,\ B \to J/\psi K,\ B \to \mu D^0$
- From the sample composition determined in the σ_{bb},
  the expected average efficiency of the tight SVX requirement:

  $\varepsilon_{\textbf{tight SVX}}$ = (24.4±0.2)%

  Measured to be (19.30±0.04)% in the dimuon sample

- Efficiency of loose SVX requirements (using Υ and J/ψ):

  $\varepsilon_{\textbf{loose SVX}}$ = (88±1)%

- What do we conclude ?
  – more background in the total sample (before SVX requirements)
  – Background is suppressed with the tight SVX selection
  $\rightarrow$ no hits in the first 2 silicon layers $\rightarrow$ large impact parameter
  – Background is not removed with looser SVX selection
  since it appears at large d_0

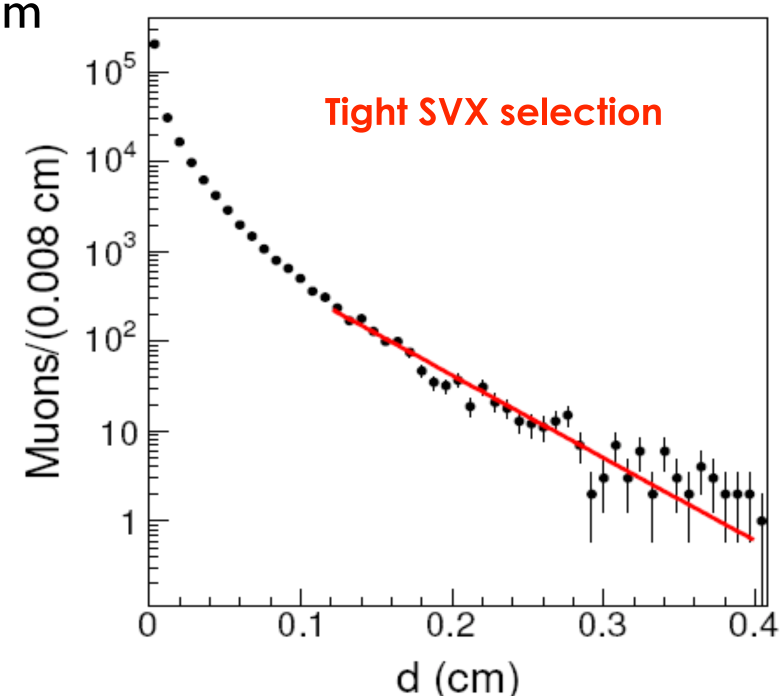
QCD events

Assume that the tight SVX selection isolates only known sources of dimuon events: we call this sample QCD

Is that reasonable?

- Charm contribution minimal for $d_0 > 0.12$ cm
- Fit d_0 distribution for muons with $0.12 < d_0 < 0.4$ cm
  - ✓ Measure $c\tau = 469.7 \pm 1.3\ \mu m$ (stat. error only)
  - ✓ PDG average *b* lifetime: $c\tau = 470.1 \pm 2.7\ \mu m$

✓ Reasonable assumption



Conclude that:

- QCD sample (selected with tight cuts) not significantly affected by additional background
- *b* contribution almost fully exhausted for $d_0 > 0.5$ cm

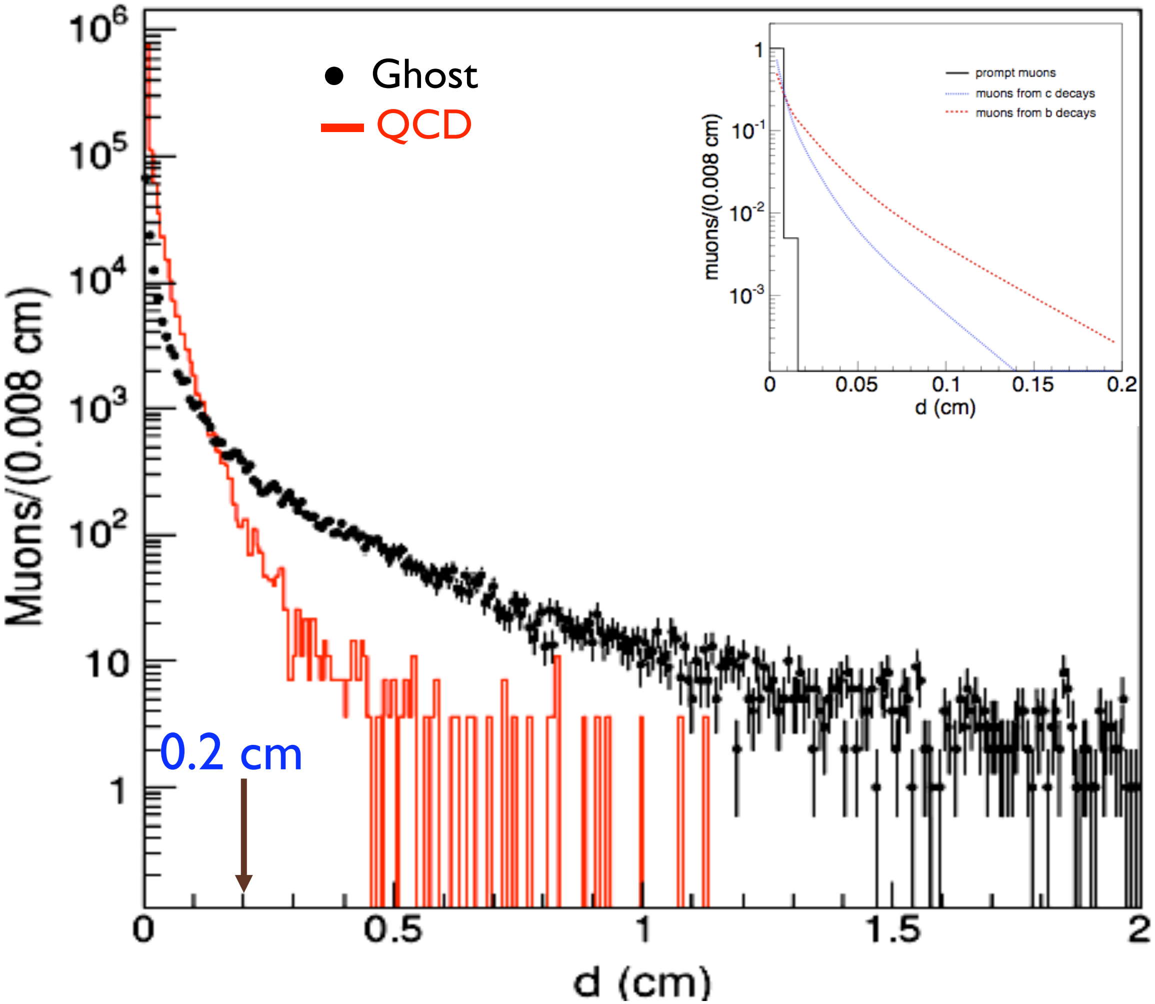
The unexpected background: Ghost events

- Start with the total sample of dimuons
- We call Ghost events the excess of events that does not pass the tight SVX requirements after accounting for the tight SVX efficiency
  - Sample definition:
    - QCD = sum of contributions determined by the fit of the $b\bar{b}$ cross section analysis [*b*, *c*, prompts]
    - GHOST = All Dimuons – QCD/$\varepsilon_{\text{tight SVX}}$

Impact parameter distribution of trigger muons

Using loose Silicon requirements

QCD vs Ghost events



- QCD sources of dimuons have d_0<0.5 cm
- Ghost events have much larger impact parameters

Counting events (742pb^{-1})

Ghost = "All" – "QCD"

Type	Total	Tight SVX	Loose SVX
All	743006	143743	590970
All OS		98218	392020
All SS		45525	198950
QCD	143743 /ε_{tight}= 589111 ± 4829	143743	143743*ε_{loose}/ε_{tight} = 518417 ± 7264
Ghost	153895 ± 4829	0	72553 ± 7264
QCD OS		98218	354228 ± 4963
QCD SS		45525	164188 ± 2301
Ghost OS		0	37792 ± 4963
Ghost SS		0	34762 ± 2301

event counting

assumption

Charge combinations

bb sample consists of 221564 ±11615 events without SVX request (194976±10458 bb events with loose SVX) – Ghost events :154K!

Plausible explanation to previous puzzles

- σ_{bb} puzzle:

  Previous measurements use selection criteria:

  - close to "loose SVX": ghost sample ~ 73K events compared to bb of ~195K $\Big\}$ R~1.3
  - no SVX req's at all: ghost sample ~ 150K events compared to bb of ~220K $\Big\}$ R~2

  - The general observation is that:

    As SVX req's are made looser, the σ_{bb} measurements increase together with the increase of the ghost sample contribution

- $\bar{\chi}$ puzzle:

  Ghost sample splits equally in OS and SS events

  $\bar{\chi}$ is measured from the ratio of SS/total using loose SVX req's

Ghost events: possible sources

✓ No dependence on luminosity, run-periods etc

Ordinary sources of events that could give rise to real or fake muons with large d_0 that miss the innermost silicon layers:

1. Mis-measured tracks
2. Hadrons mimicking a muon (punch-through)

   evaluated with data using $D^0 \to K\pi$
3. Decays in-flight of $K^{\pm}$, $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$

   evaluated using Monte Carlo (Herwig)

   $\Big\}$ ~57000 evts (items 2–3)
4. Decays of long–lived hadrons:

   $K_S^0 \to \pi^+\pi^-$ $\quad \Lambda \to p\pi$ evaluated using data $\Big\}$ ~12000 evts
5. Secondary interactions in detector material

   secondary products with large d_0

<u>We can explain 50% of the total ghost sample (153895 evts)</u>

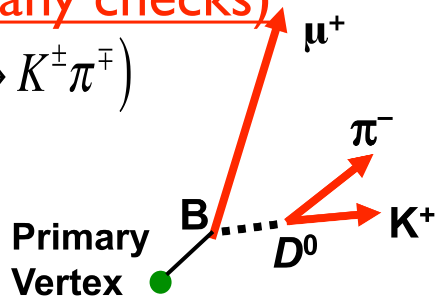
Ordinary sources of Ghost events

1. Track mismeasurements: (many checks)

Look at events with $\mu^{\pm} + D^0(\to K^{\pm}\pi^{\mp})$

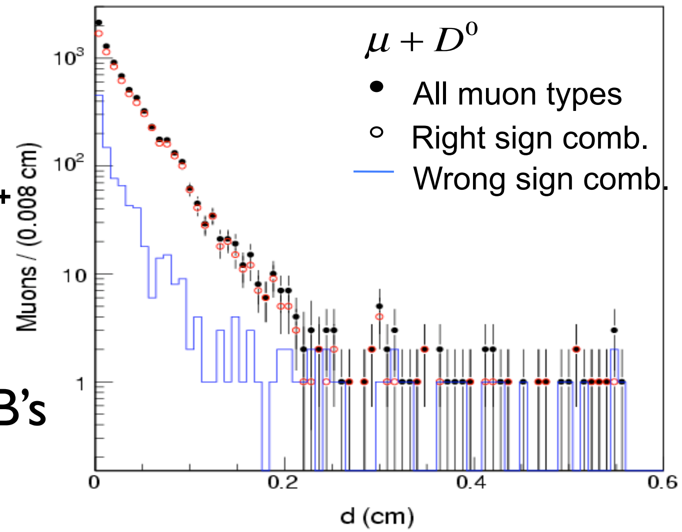
Events mainly due to $b\bar{b}$

Combinatorics for D^0:



Right: μ, K have same charge

Wrong: μ, K have opposite charge



✓ No long tails in $d_0(\mu)$ - consistent as coming from B's

➢ Wrong sign comb. show the low level of fakes

2. Hadronic punch-through – fake muons:

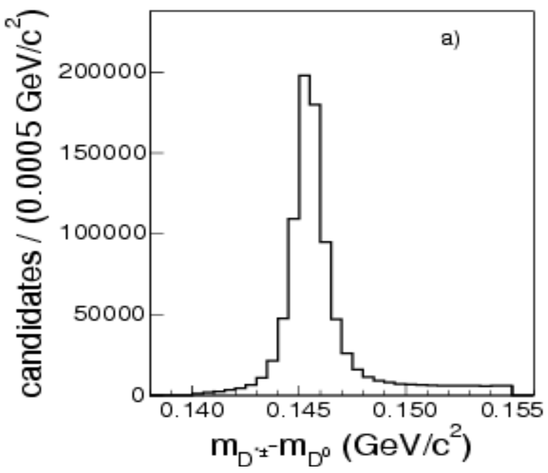
Measure probability per track that a π or K will punch–through the calorimeter

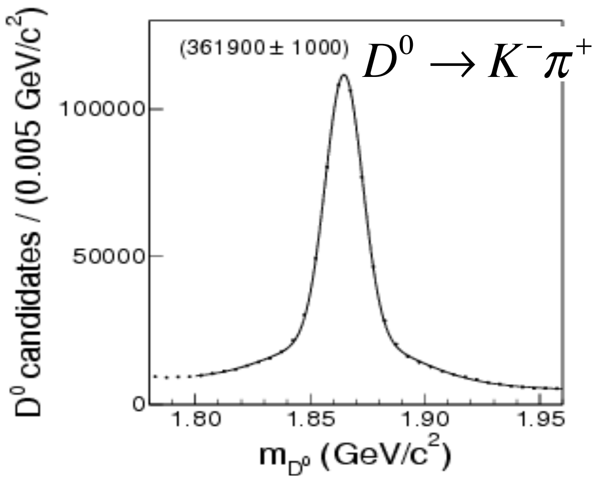
Reconstruct $D^{*+} \to D^0\pi^+$

with $D^0 \to K^-\pi^+$

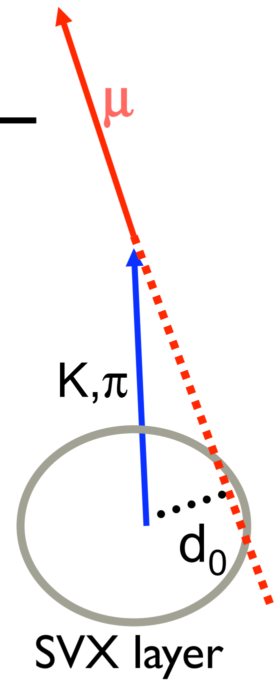
➢ D^{*+} uniquely identifies π, K

Measure the rate hadrons are found as muons





Ordinary sources of Ghost events



3. Decays-in-flight :

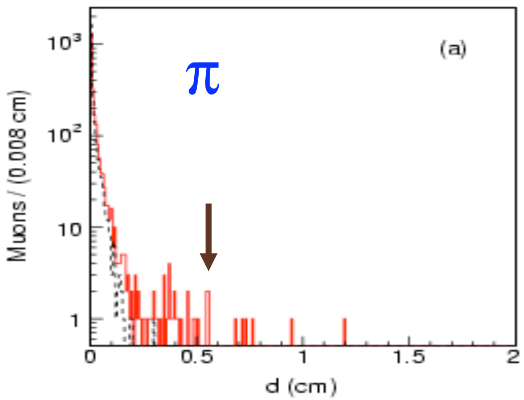
- Measure the probability that K and π decays produce CMUP muons (trigger muons) using generic hard scattering MC simulation [Herwig].
- Probability per track that a hadron yields a trigger muon is $\begin{cases} \pi: 0.07\% \\ K: 0.34\% \end{cases}$
- Normalize this rate from Herwig MC to measured *bb* cross section

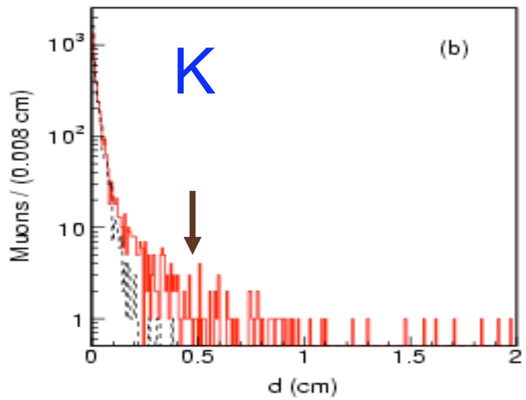
Prediction: 57000 of ghost events due to decays-in-light

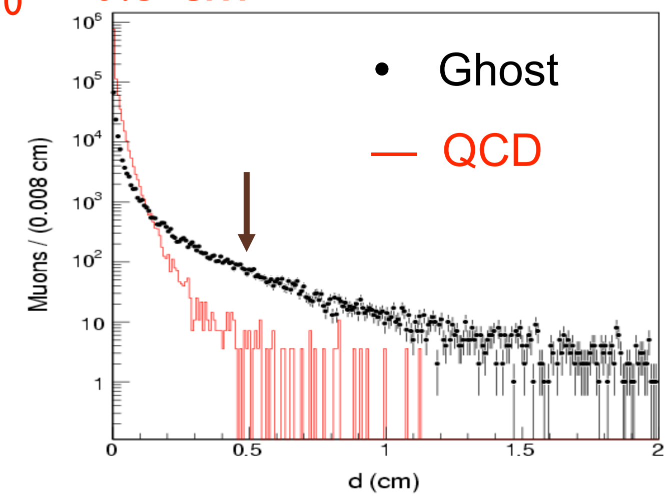
➢ Large uncertainty on prediction: (particle fractions, momentum spectra, σ_{bb}, …)

Yield of in-flight decays explains more than 35% of the ghost sample

However, only 10% of the decays-in-flight have d_0 > 0.5 cm





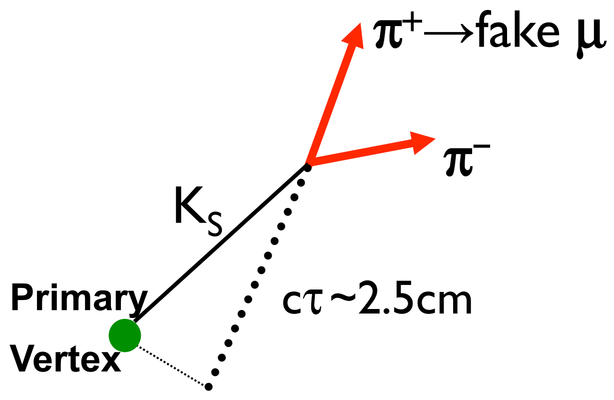


Ordinary sources of ghost events

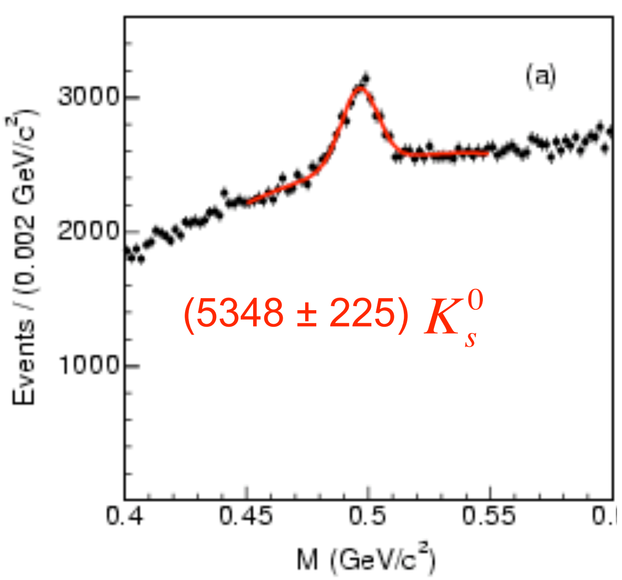
4. K^0_S and hyperon decays:

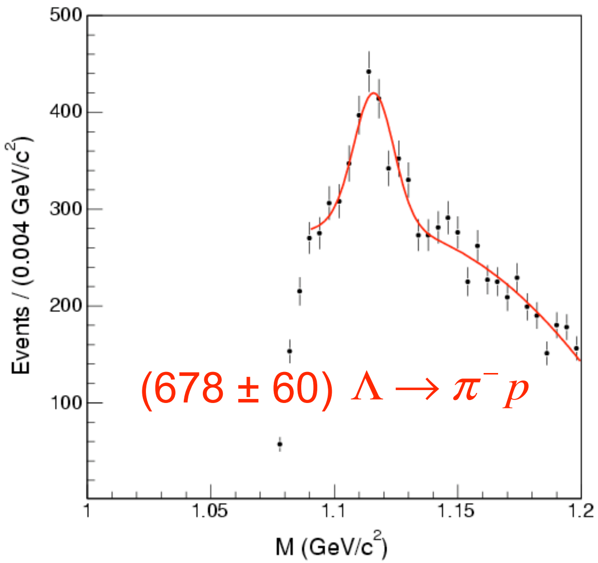
- Look for μ + track with track p_T > 0.5 GeV/c
- Assume μ and track are π

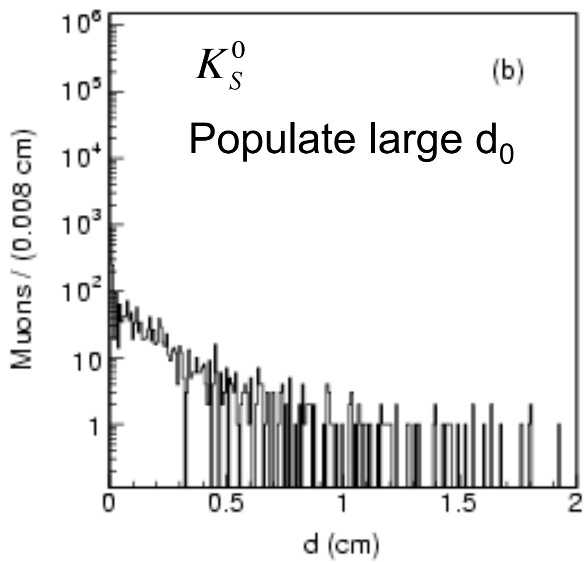
➢ Kinematic acceptance x reconstruction efficiency ~ 50% (MC)



❑ Approximately 12000 ghost events (8%) are due to these decays





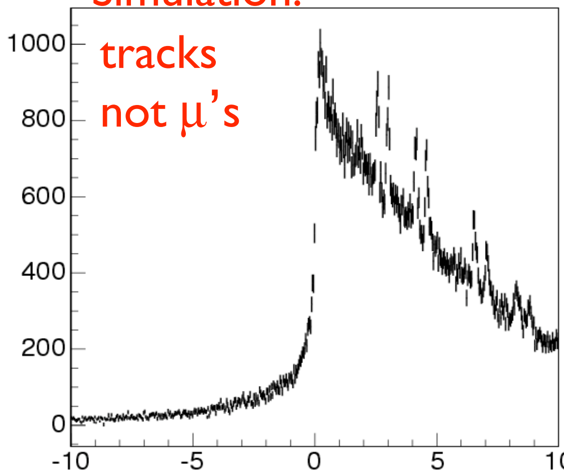


Ordinary sources of ghost events

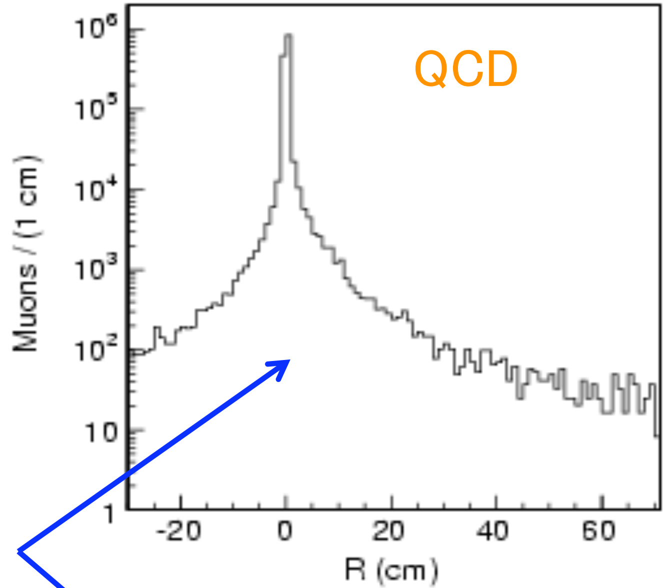
5. Secondary Interactions:

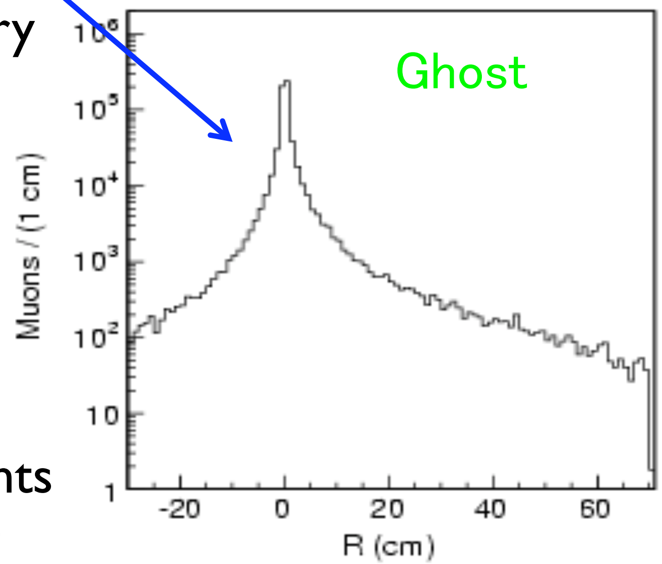
- Look for μ + tracks with track p_T>0.5 GeV/c
- Tracks in a 40^0 cone around the muon
- Looking at the radius of the two tracks intersection vertex we should find spikes where there is concentrated material:

Simulation:



No visible spikes of multi-prong secondary interactions





- We can not exclude contribution to ghost events from elastic or quasi-elastic nuclear scattering in the detector material

Search for additional muons:

Interesting for several reasons

- Events due to secondary interactions or decays-in-flight are not expected to contain significant amount of additional muons.
- If ghost events were like normal QCD events with some mismeasured trigger muons, the rate of additional muons should be as in QCD events
- The excess of the low mass dileptons from Run I might be related to ghost events
- Events with additional muons should be contributed mainly by b-sequential decays. Expect a contribution from muons faked by hadrons which is not simulated but is estimated from data.

Search for additional muons:

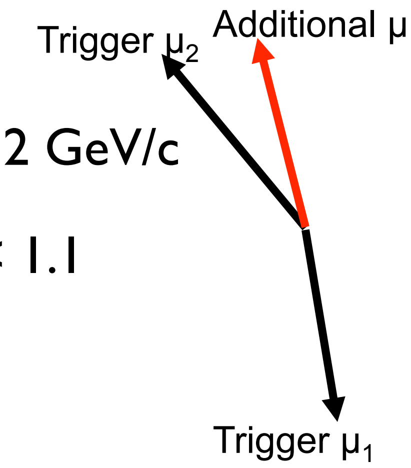
- Look for additional muons:

  Around each trigger muon

  Use all central muon detectors (CMU+CMP+CMX) $\left\{ \begin{array}{l} p_T > 2\ \mathrm{GeV}/c \\ |\eta| < 1.1 \end{array} \right.$

  Require initially $M_{\mu\mu} < 5\ \mathrm{GeV}/c^2$

  - Requirements designed for maximal acceptance at the cost of higher fake rate



- In data, 9.7% of the events contain an additional muons

1. Check the yield of additional muons in some class of events:
   - $\Upsilon(1S)$ events: 0.9% with an additional muon (fakes from underlying event)
   - K^0_S events: 1.7% with an additional muon (mostly fakes)
2. Check the efficiency of tight SVX req's on trigger muons:
   - Expect it to rise from $\varepsilon_{\text{tight SVX}} = 0.193 \rightarrow 0.244$ expected for QCD
   - Instead it is found lower: 0.166 !
     - The ghost event contribution increases from 20.9% to 32%

- Ghost events contain more additional muons than QCD events

Low mass dimuons

Compare invariant mass in data and simulation that includes fakes

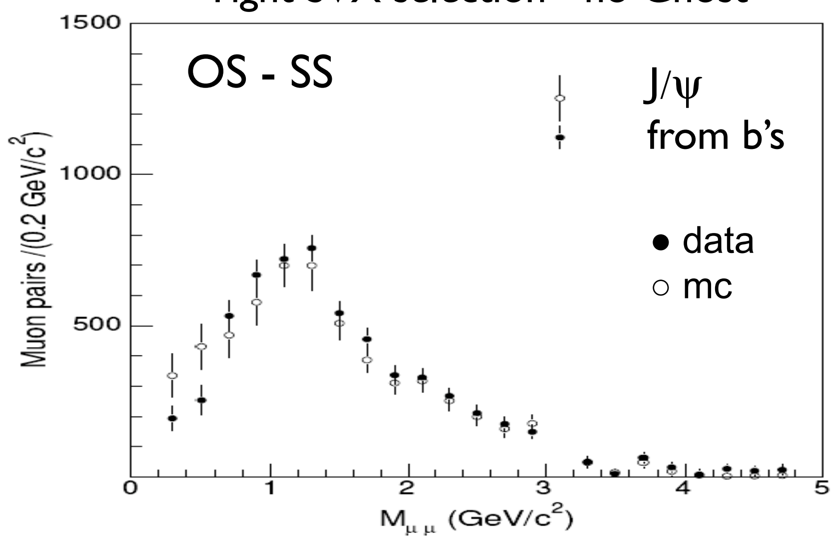
Tight SVX : Data: 6935±154; MC: 6998±239

on trigger muons

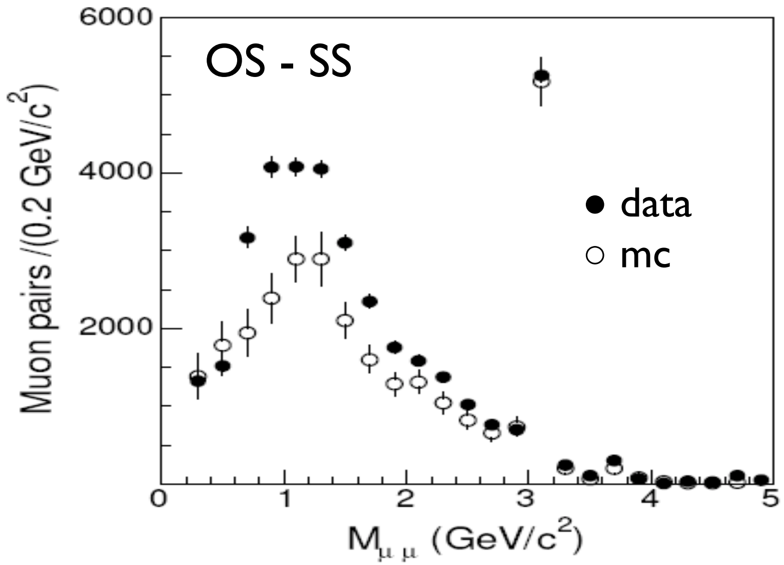
no Si req's on add. muon

Conclusion: σ_{bb}, h.f. simulation, fake muons — well understood

Tight SVX selection - no Ghost



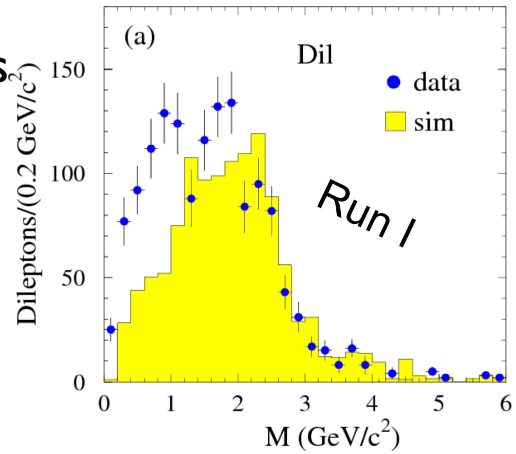
- Entire sample: no SVX req's :



✓ Excellent agreement on the J/ψ prediction

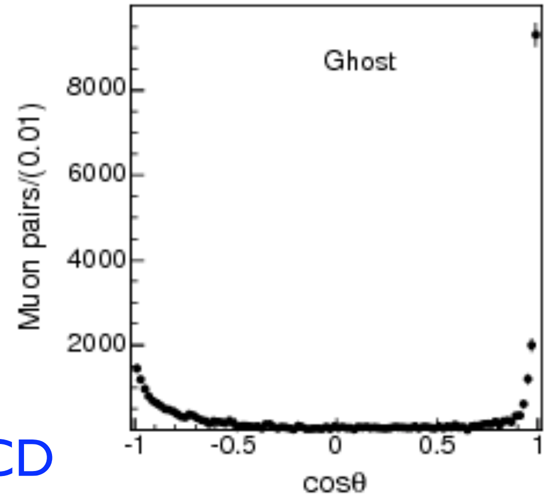
➢ Clear excess at low mass not seen with tight SVX associated with ghost

Excess: 8451 ± 1274 evts



Extra muon/tracks in ghost events

Most of the additional muons in ghost events are within a cone of $\cos\theta > 0.8$ around the trigger muon



- Count tracks ($p_T > 2$ GeV/c, $|\eta| \leq 1.1$) inside cones

  Yield of charged tracks in ghost events 2x the one in QCD

- Count muons inside cones (Ghost events)

  After accounting for fakes there are approximately 9.4% real muon combinations with SS or OS charge compared to 2.1% in QCD evts.

  Yield of additional muons in ghost events 4x the one in QCD evts

Muon multiplicity in a $\cos\theta > 0.8$ cone

First surprise!

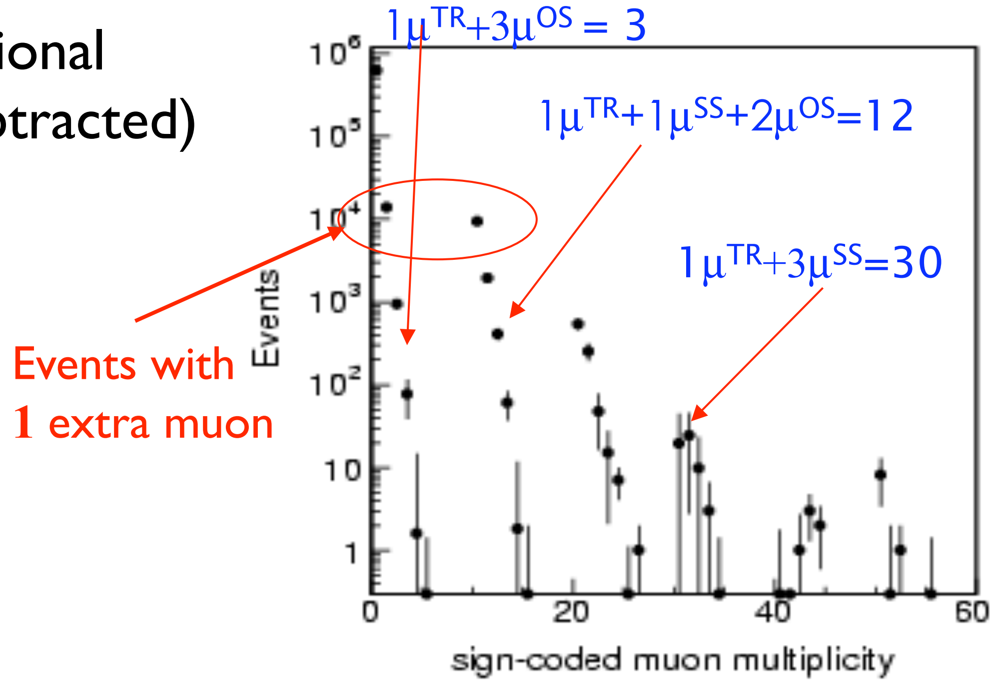
Plot shows the number of additional muons in a single cone (fake subtracted)

We count additional muons relative to the trigger muon:

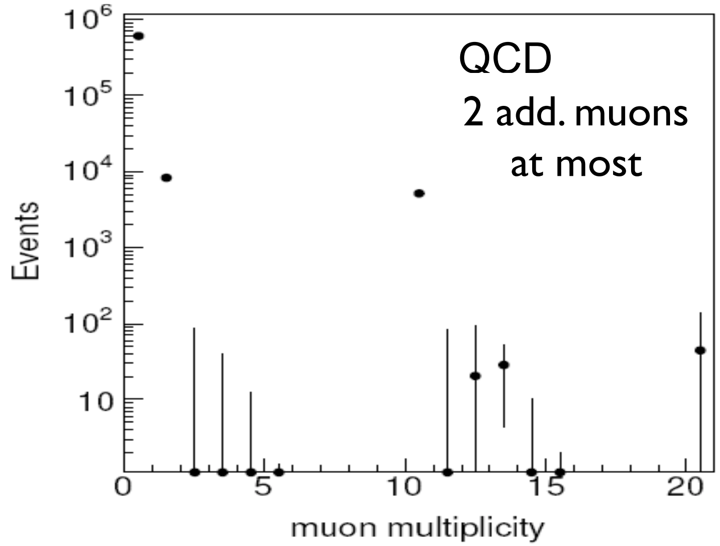
$$\mathcal{M} = N_{OS} + 10N_{SS}$$

$\forall$ OS μ: $\mathcal{M} = +1$

$\forall$ SS μ: $\mathcal{M} = +10$



For example:
in a cone of μ^+ we find $2\mu^-$ and $1\mu^+$:
It corresponds to bin 12

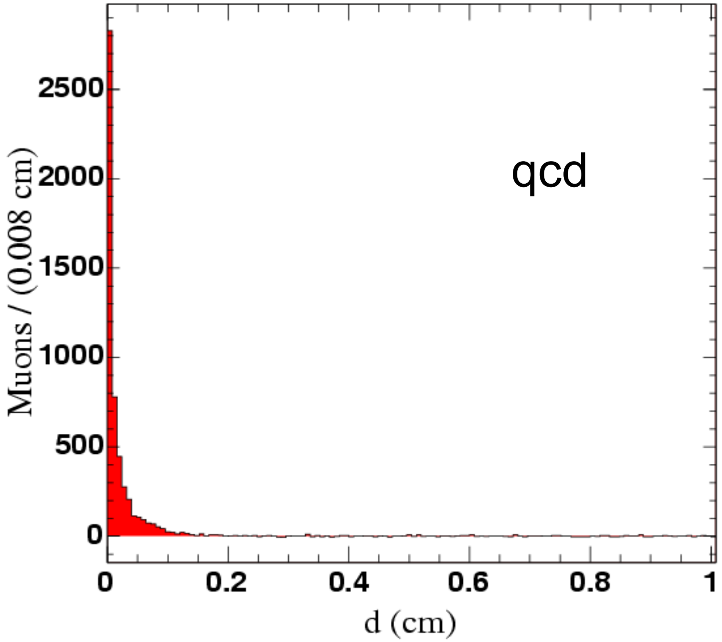


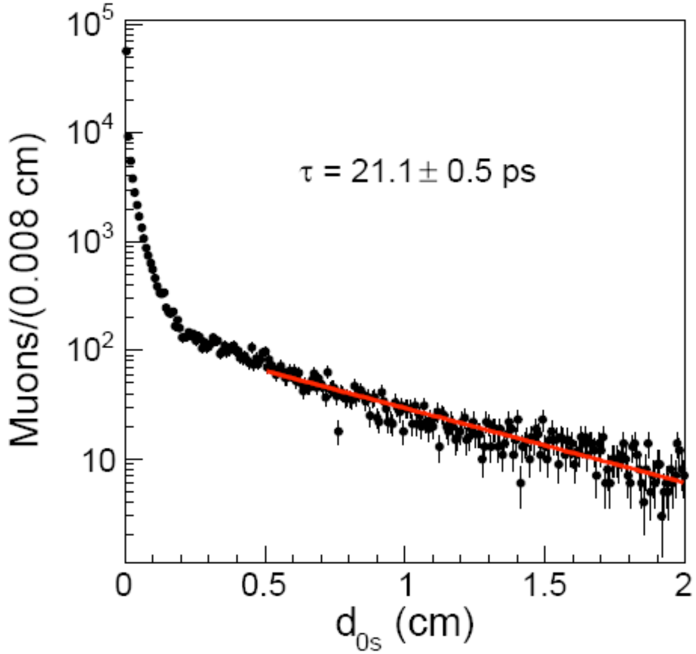
Some ghost events have very large muon multiplicities - 3 or 4 muons in a cone

Additional muons: impact parameter

Second surprise!

- The impact parameter of the additional muons is consistent with that of initial muons - large tail

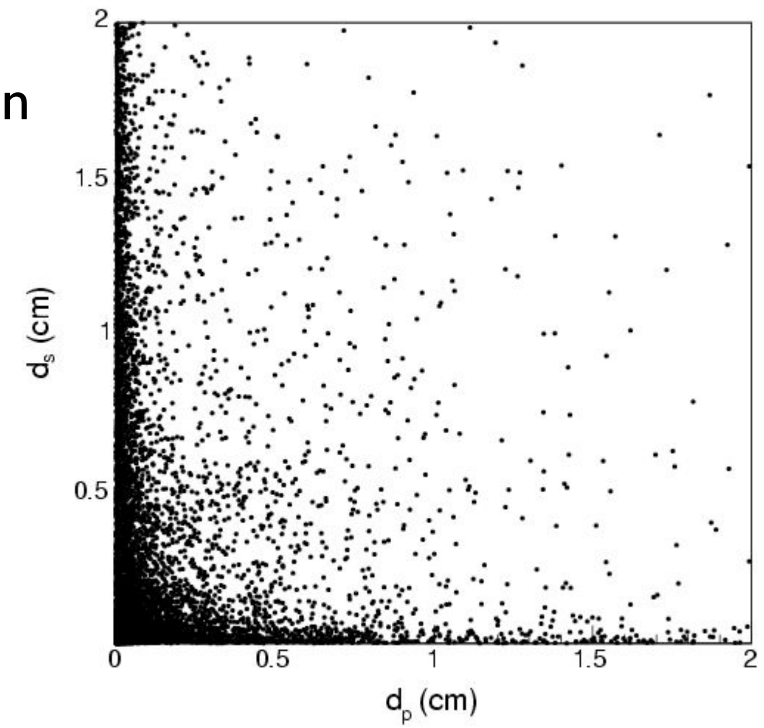




Additional CMUP muons in ghost events

- The salient features of ghost events, like additional track and muon multiplicity higher than that of QCD events, remain even when requiring the additional muon to be CMUP (very pure)

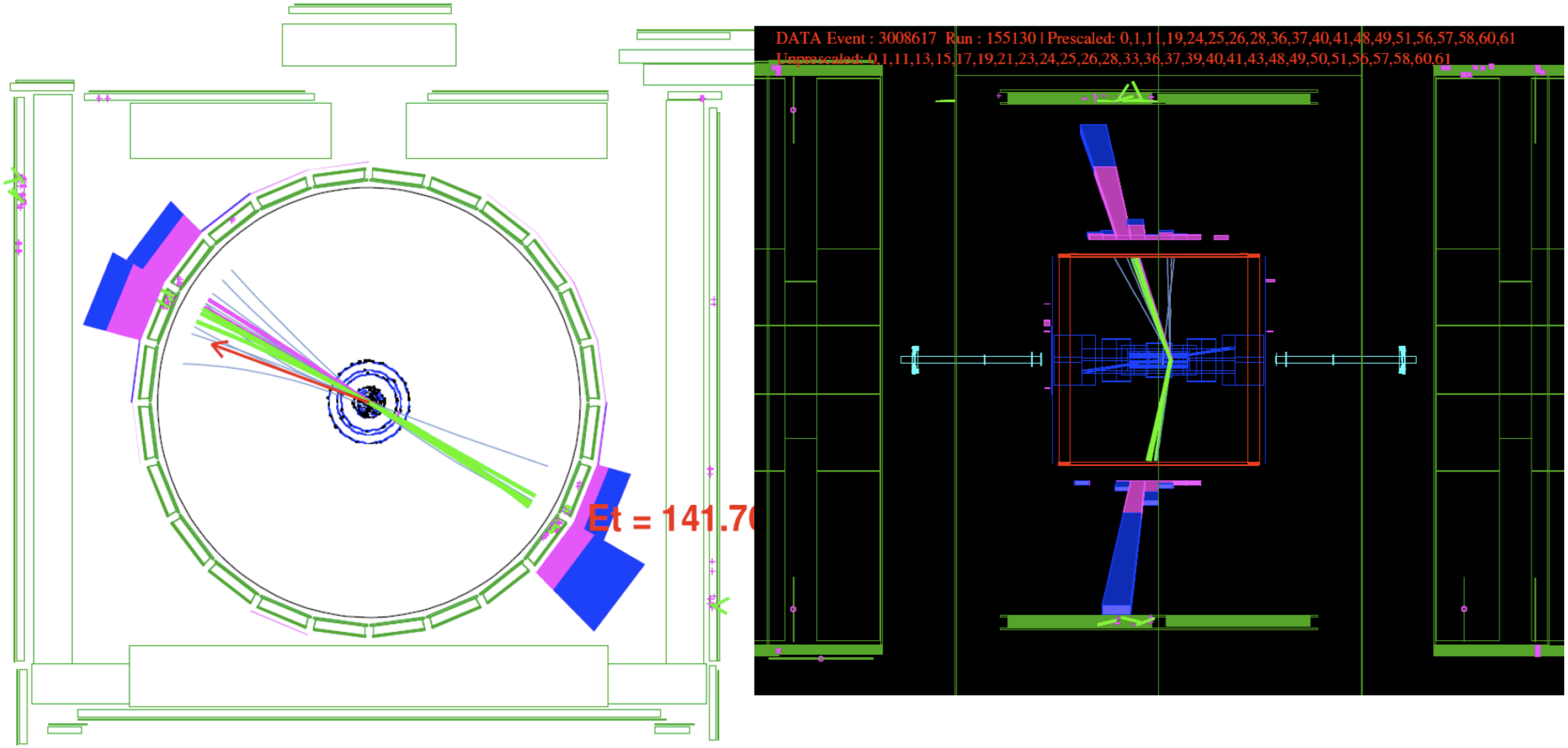
- The large impact parameter distribution of additional muons is consistent with the trigger muons



Conclusions

- We observed an excess of events in the dimuon trigger sample that we do not understand, called Ghosts
- The size of the excess is comparable to the *bb* contribution
- They offer a plausible explanation of all the previously observed inconsistencies and puzzles that have affected measurements of b-quark production and decay at the Tevatron for more than a decade
- A piece of the ghost sample contains events with some unique properties which we can not explain and we are not yet able to rule out known processes:
  - contain high muon and track multiplicity
  - The additional muons exhibit large impact parameter well above the one of additional muons in the QCD sample
- Contrary to the unexpected features of the ghost sample we understand very well the QCD sample in terms of detector, reconstruction and physics

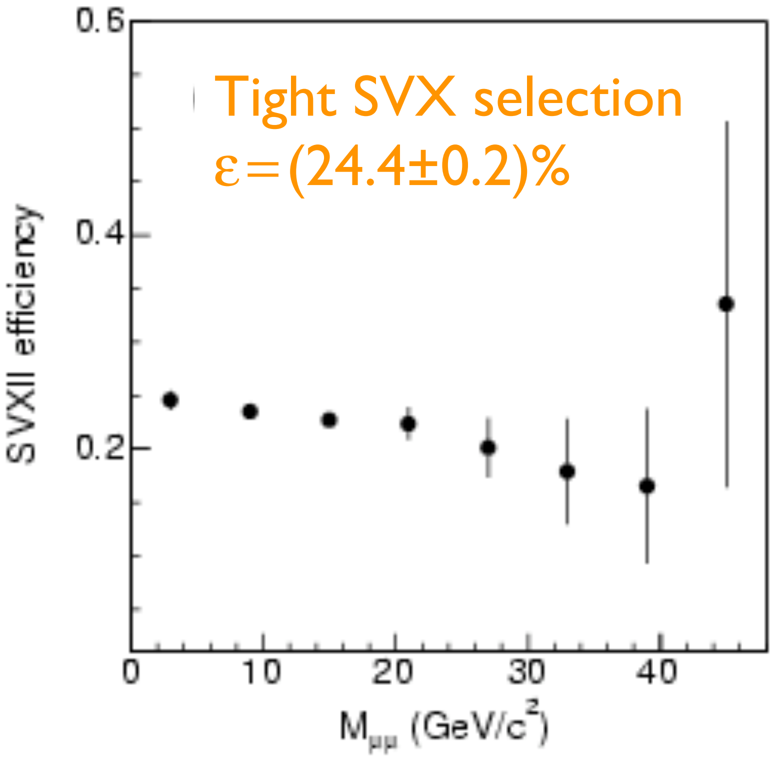
Event display

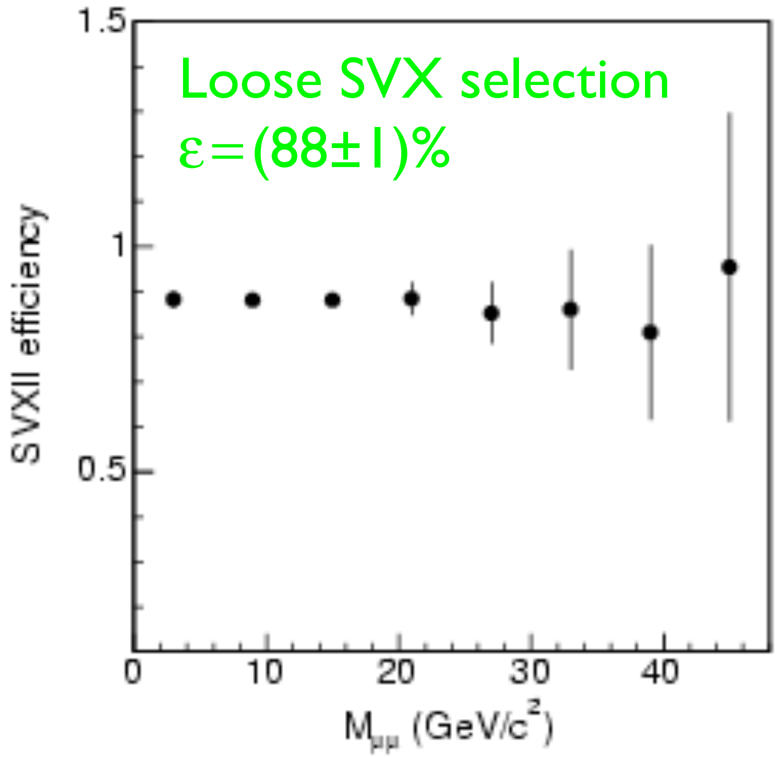


Backup

Silicon efficiency

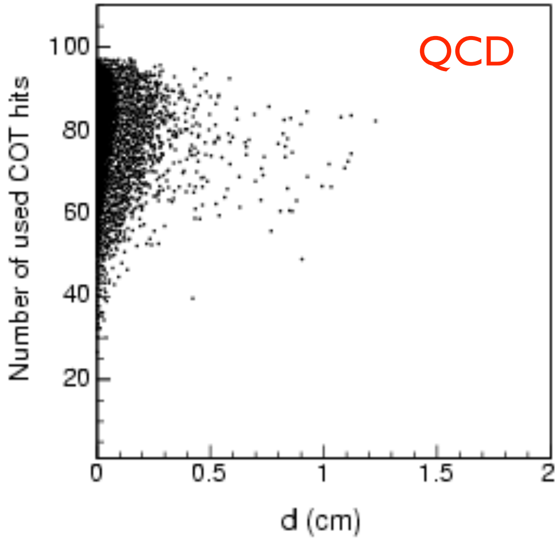
- Silicon efficiency from QCD simulation

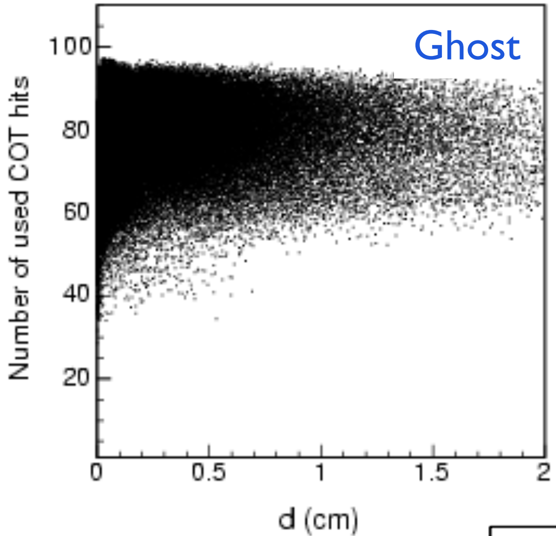




Tracking quality

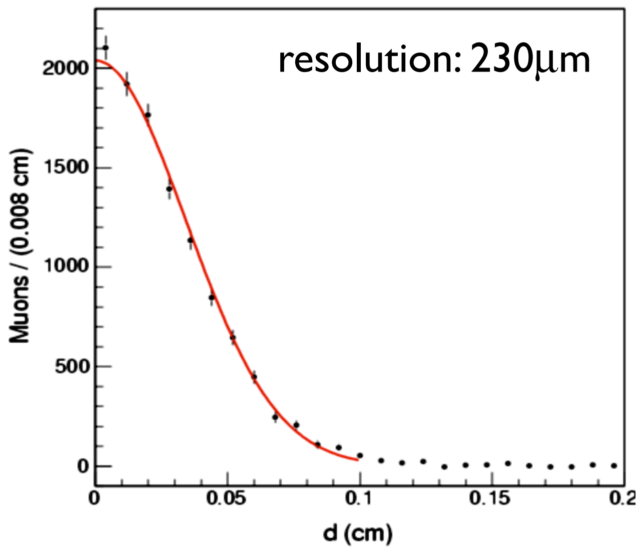
- Tracks reconstructed with hits in at least 20 layers of the central tracker are considered good





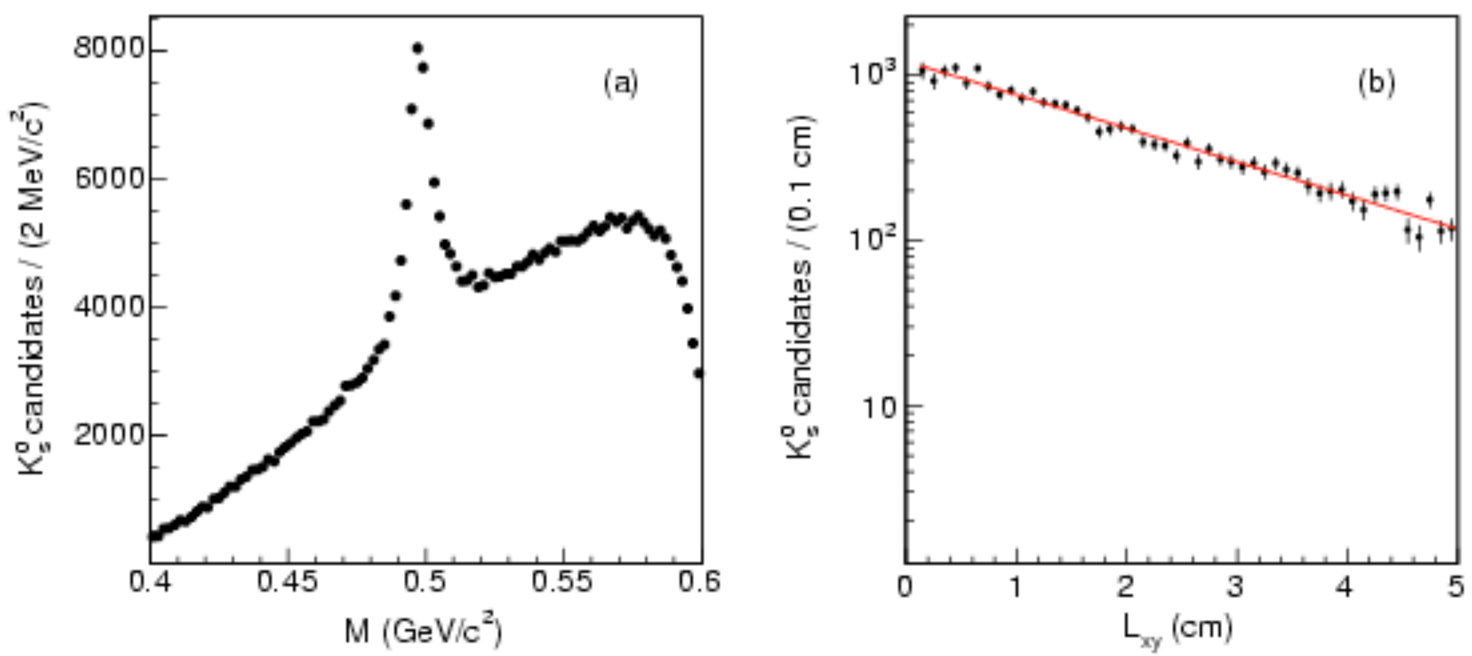
- Use $\Upsilon \rightarrow \mu^+\mu^-$ where muon tracks have no silicon hits.
- Distribution exhausts after 0.12cm

✓ Impact parameter distribution of muons in ghost events is not due to tracks reconstructed with no silicon hits



Tracking quality – Using K^0_S

- Use $K^0_S \rightarrow \pi^+\pi^-$ reconstructed in the dimuon sample
- Use tracks with p_T>0.5 GeV/c , $|\eta|$<1.1 and opening angle < 60^0
- 3-d vertex constraint and correct the L_{xy} for the Lorentz boost
- Fit of L_{xy} returns a lifetime of 89.5ps



Additional muons by detector type

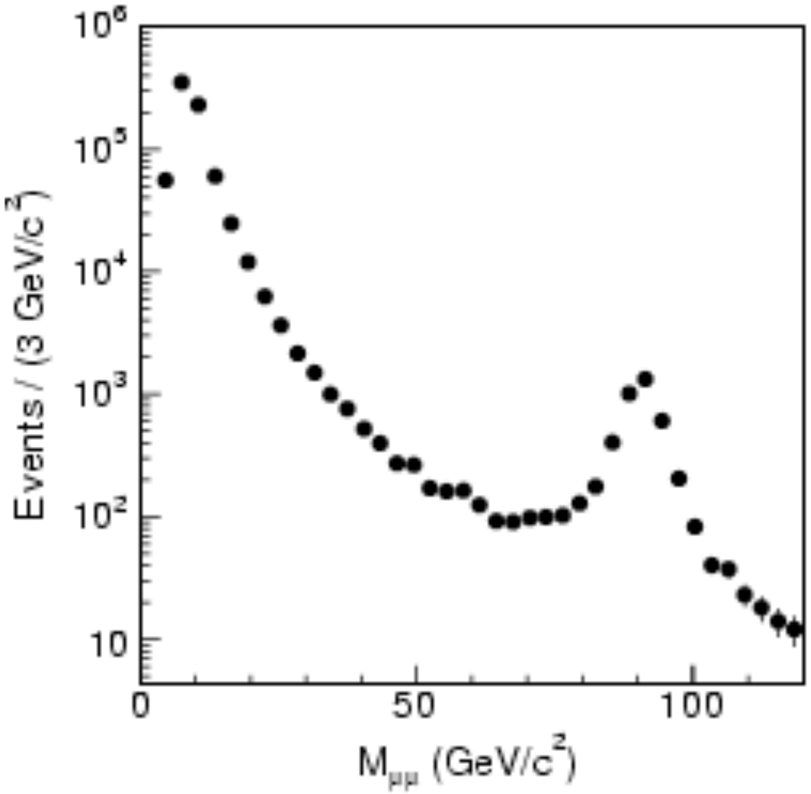
- Compare the fractional distribution of additional muons according to the detector type the muon was identified.
- Compare to QCD expectations where we predict the rates of additional muons.

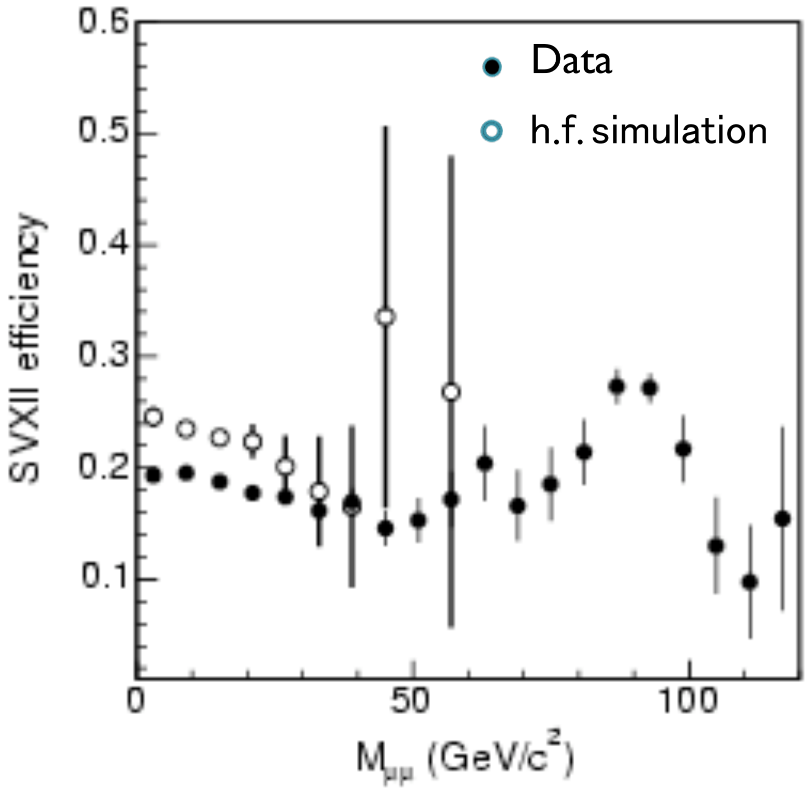
Sample	CMUP	CMU	CMP	CMX
QCD	17.0±0.4	53.0±0.7	26.0±0.5	4.0±0.2
Ghost	14.0±0.8	60.0±1.4	24±1	2.0±0.4

➢ The response of the muon detector is an unlikely candidate to explain the large excess of additional muons in ghost events

Heavy flavor with large Lorentz boost

- It is counterintuitive to have heavy flavor with large boost and large d_0
- Use all dimuons (no mass cut).

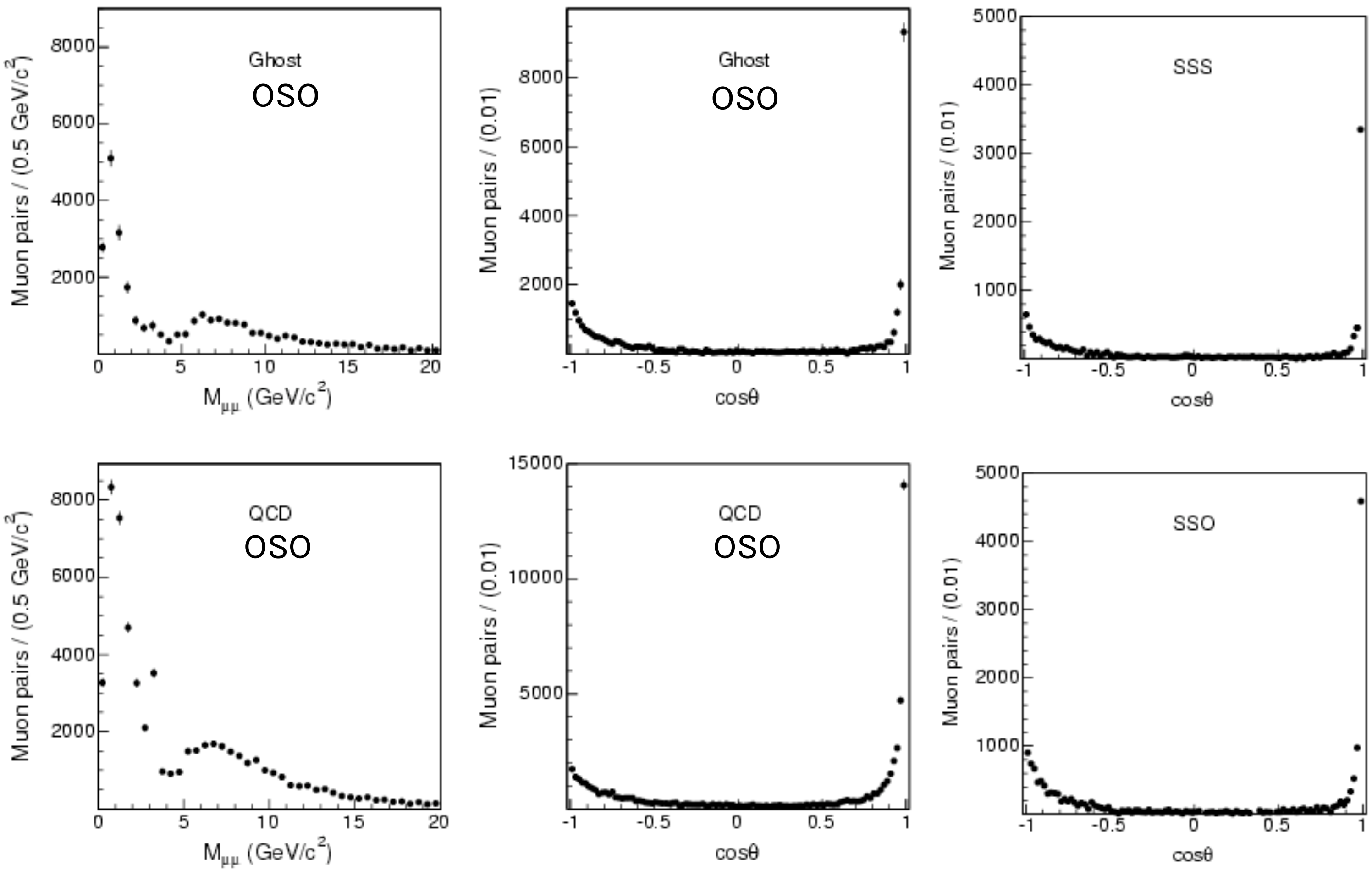




Additional muon – remove low mass requirement

Search for additional muons without an invariant mass cut requirement
Combine the additional muon with the trigger muon of opposite sign
if the two trigger muons have opposite charge (OSO)

For same sign initial dimuons combine the additional muon randomly (SSO and SSS)



Observation:

Additional muons are within a cone of cos θ >0.8 around the trigger muon

Extra muon/tracks in ghost events – No low mass cut

- There are 1131090 QCD evts and 295481 ghost evts
  - Count tracks (p_T>2 GeV/c, $|\eta|\leq 1.1$) inside cones

Topology	All	SVX	QCD	F_{QCD}	Ghost	F_{ghost}
OS	1315451	207344	849770 ± 6965	0.75	465860 ± 6965	1.58
SS	893750	140238	574745 ± 4711	0.51	318004 ± 4711	1.08

Yield of charged tracks in ghost events 2x the one in QCD

  - Count muons inside cones (Ghost events)

Topology	QCD	Ghost	F_K	F_π
OS	54545±447	28692 ± 447	15447 ± 210	9649 ± 131
SS	30053±246	20180 ± 246	10282 ± 137	6427 ± 81

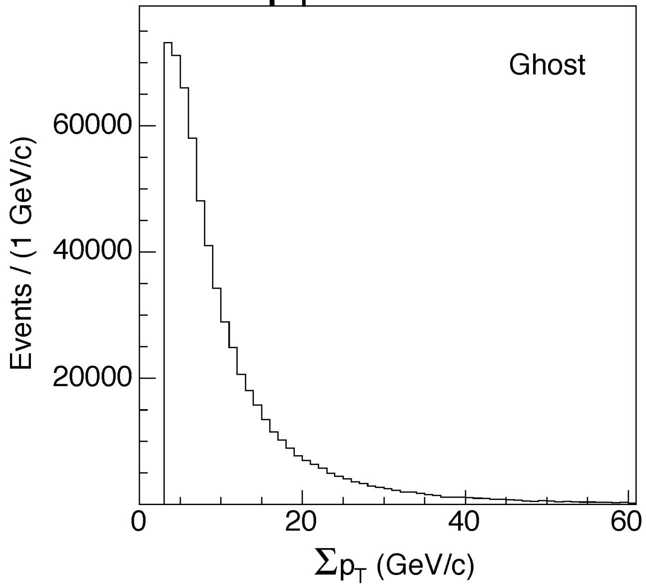
After accounting for fakes there are approximately 28000 real muon combinations with SS or OS charge (9.4%) compared to 24492 (2.1%) for QCD evts.

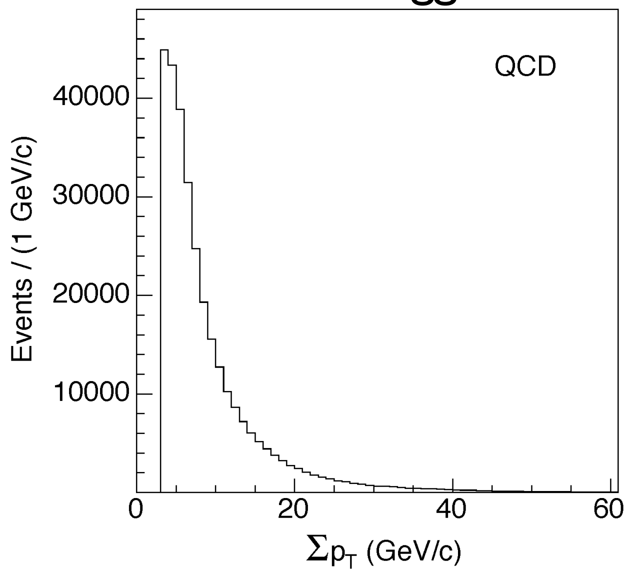
Yield of additional muons in ghost events 4x the one in QCD evts (2.1%)

Correlated punch-through

- Traditionally searches for soft muons performed by CDF estimate the fake muon contribution using a per-track probability.
- It has been argued that ghost events could be due to a breakdown of this method in presence of events with high E_T jets with many tracks not contained in the calorimeters. It could be true but there is no control sample to study it
- Tightening selection criteria, features remain in the cost of reduced acceptance
- We would have observed this effect also in the QCD control sample since the energy flow in the jet is similar

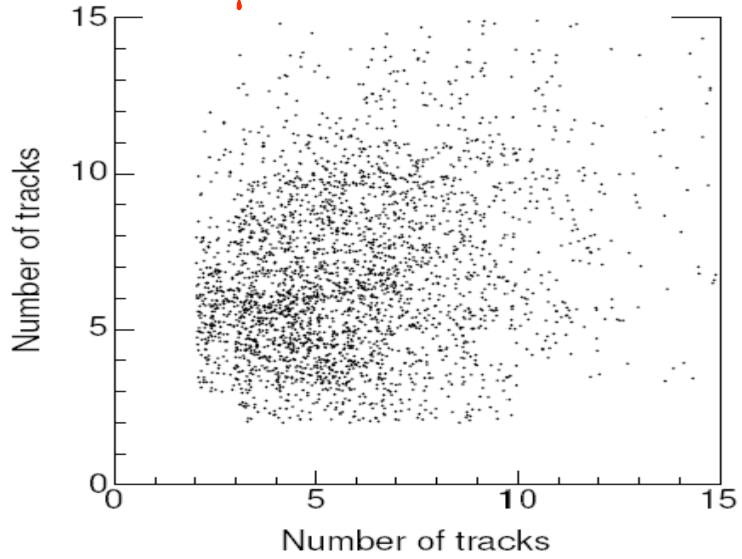
Track Σp_T in cones of $\cos\theta > 0.8$ around a trigger muon





Cone correlations

≥ 2μ in both cones



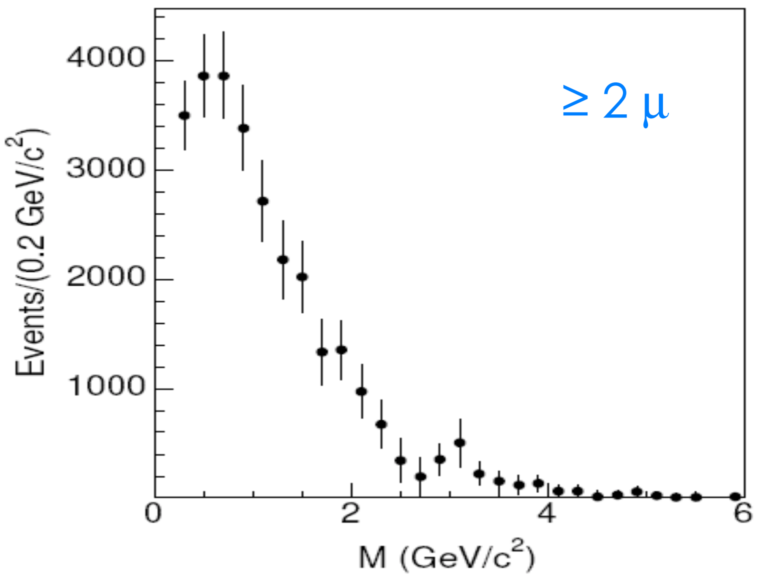
Ghost Events

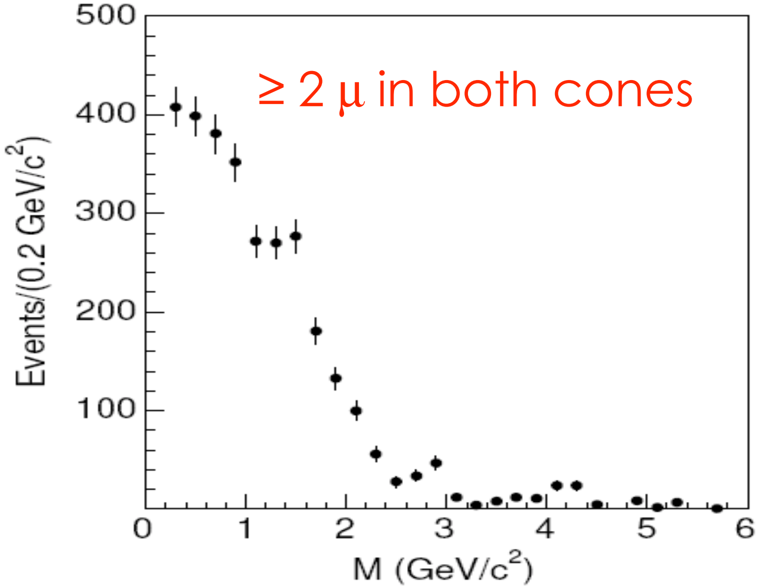
27790 ± 761 cones with ≥2μ (1)

4133 ± 263 cones with ≥ 3μ

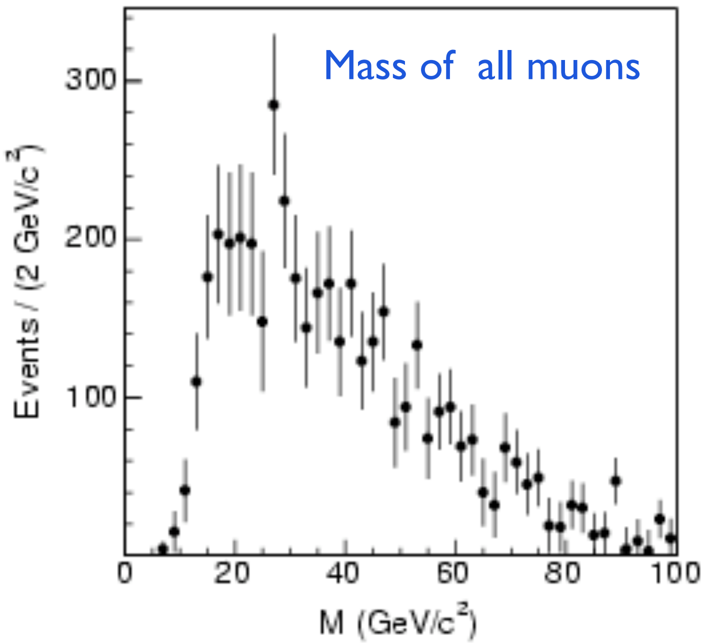
3016 with ≥ 2μ in both cones (2)

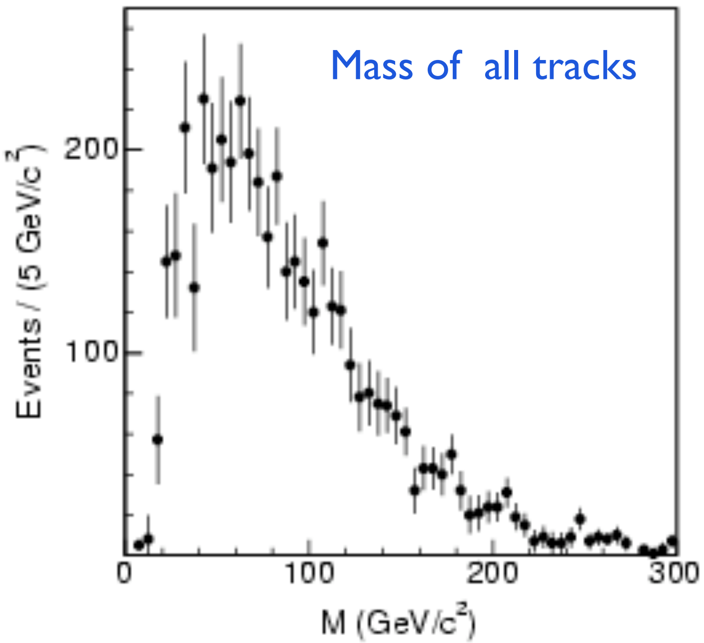
Ratio of (2)/(1) = 0.11
comparable to what expected
for double parton production (jets)





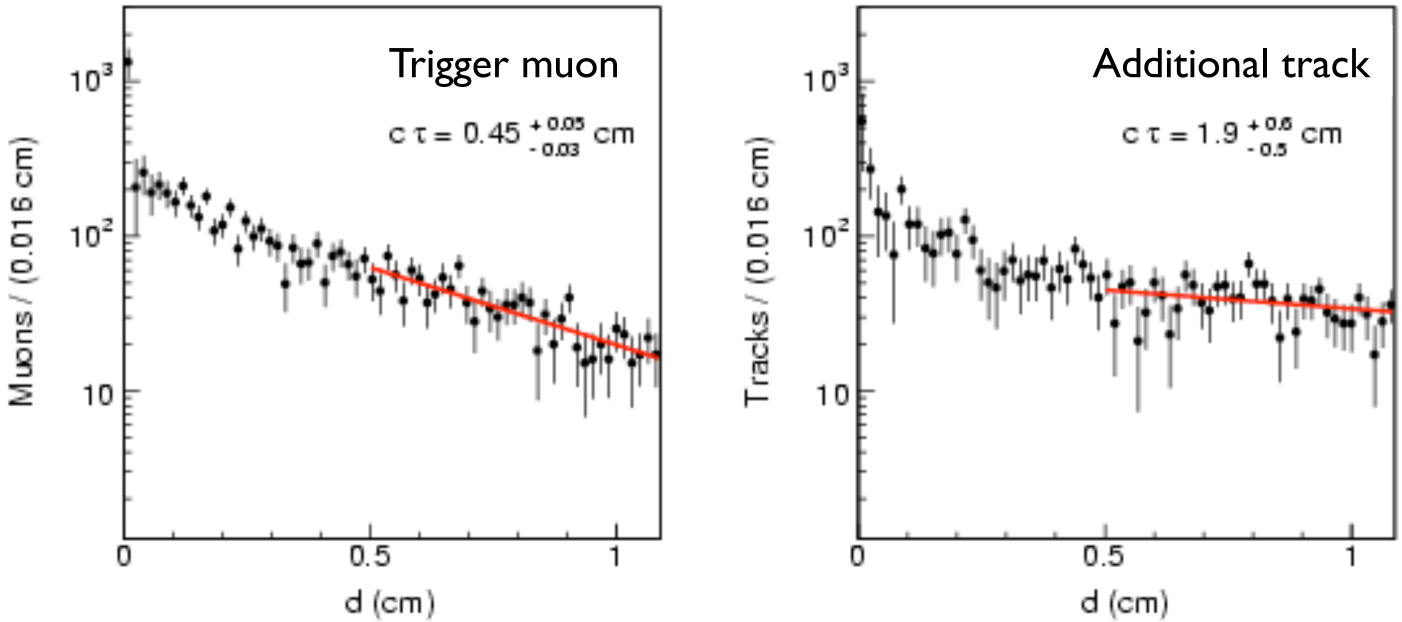
Ghost events with ≥ 2μ in both cones





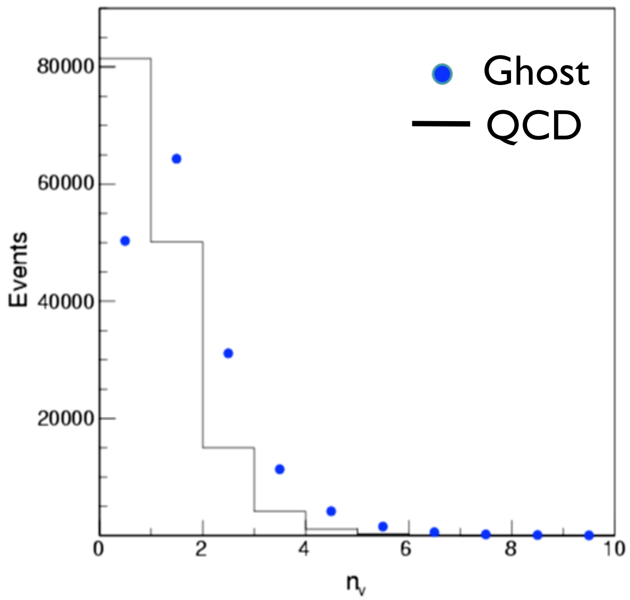
Effect of Trigger bias on d_0 distributions - K^0_S case

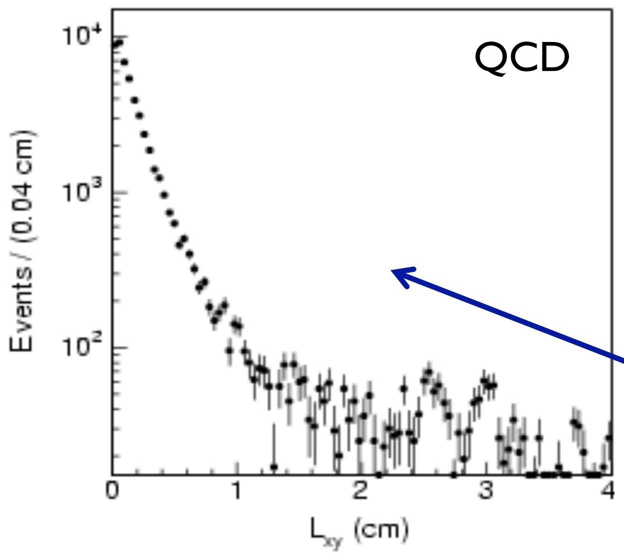
- Use $K^0_S \rightarrow \pi^+\pi^-$
- One π punches through the calorimeter and gives the trigger muon (CMUP)
- Look for an additional track with p_T >2 GeV/c in 40^0 around the trigger muon
- Distribution of d_0 for trigger muon and track after side-band subtraction

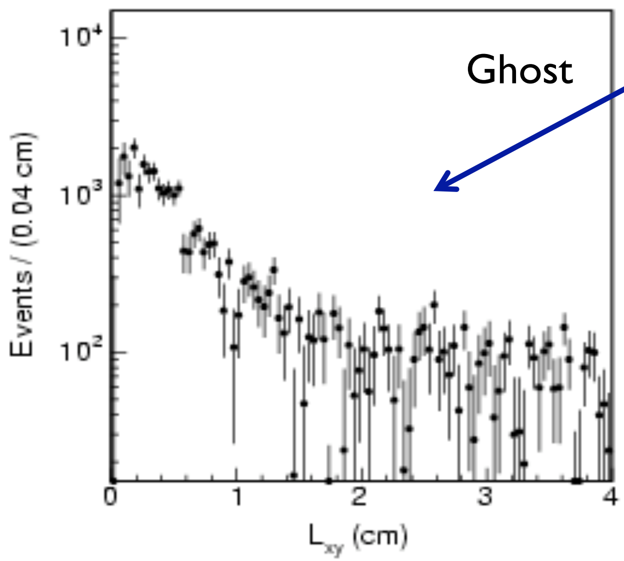


Testing the lifetime hypothesis

Search for pairs of tracks in a cone of $\cos\theta > 0.8$ around a trigger muon with $p_T > 1$ GeV and opposite charge



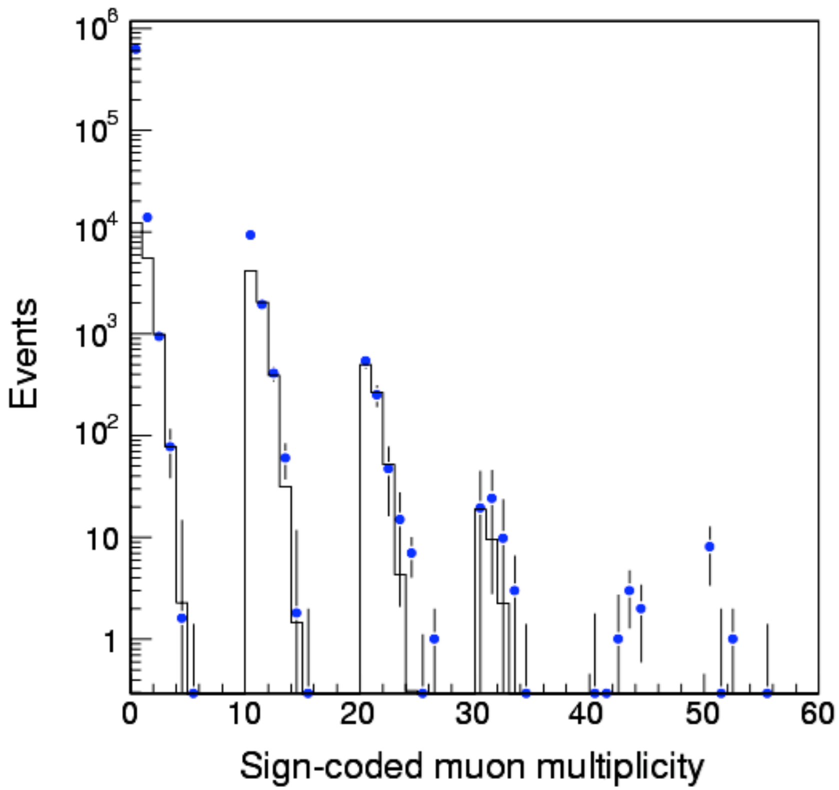




Background is removed by subtracting the corresponding negative L_{xy} distribution

Hypothetical conjecture: [arXiv:0810.5730]

Fraction of the ghost events is due to an object h_1 that is produced with transverse momentum much larger than its mass and decays into 8 taus



- Remove fakes assuming tracks are π
- Histogram corresponds to a toy MC of $8\,\tau\to\mu$ with branching fraction 17.4% and ε^{μ}_{trig}=50% and $\varepsilon^{\mu}_{add.}$=83.8%.
- Assume $\varepsilon_{kin.}$=1
- Toy MC of $4\tau^{+}-4\tau^{+}$ normalized to the data for bins ≥11.
- Accounts for approximately 5% of the ghost events (13200 events)

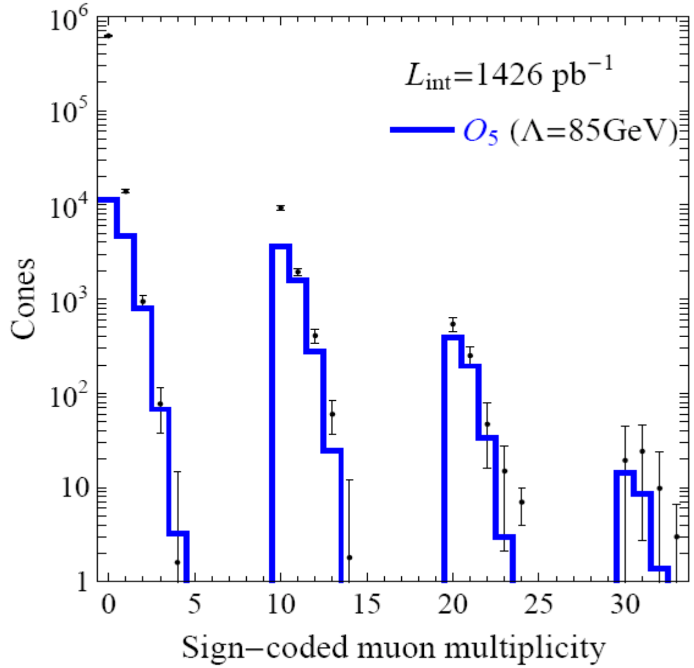
Barbieri et al. [arXiv:0902.2145]

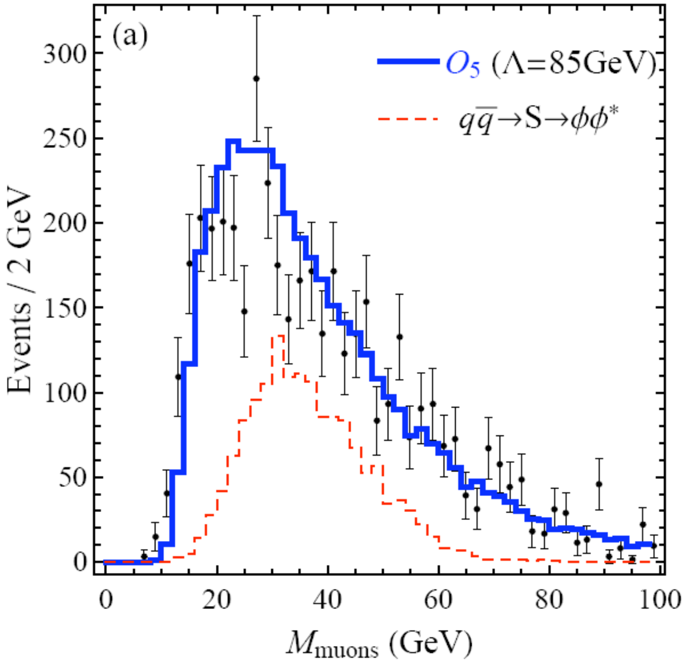
$$O_5 = \frac{1}{\Lambda}(\bar{q}q)|\phi|^2 \qquad p\bar{p} \to \phi\phi$$

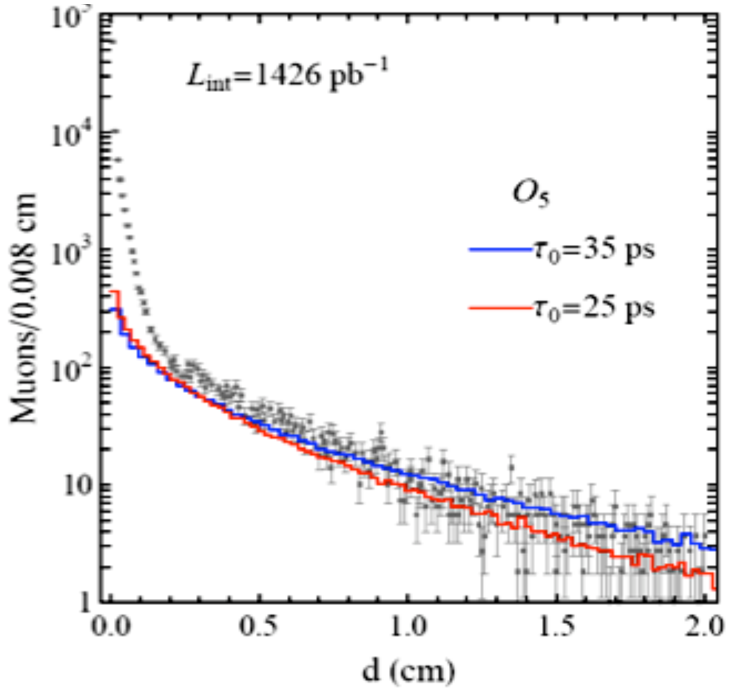
$$\phi \to 2\phi_1 \to 4\phi_2 \to 8\tau$$

$$m_\phi = 15GeV$$

$\phi_2 \to \tau\bar{\tau}$ with a long lifetime







Run I – $\bar{\chi}$

- Muons could originate as far as 5.4cm